Substorm Onset in the Magnetotail

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Known signatures of the expansion phase onset in the magnetotail are summarized and discussed. A model is suggested for the nature of the multiple onset events. The importance is emphasized of observing the low-latitude magnetotail at $|X| \sim 10$ to $15 R_E$ at and shortly before the onset of the expansion phase.

1. Introduction

It has become widely accepted that the magnetotail is the region of vital importance in the substorm physics. It is in the magnetotail that the energy obtained from the solar wind is stored, and it is also in the magnetotail that the stored magnetic field energy is converted explosively to the kinetic energy of charged particles. From this view point the substorm onset in the magnetotail should be a clearly definable concept; the time when the magnetic flux content of the magnetotail suddenly begins to drop and the acceleration process starts to operate should be the moment when a substorm starts, or stated more explicitly, when a substorm enters the expansion phase.

The idea is simple and clear, and there wouldn't be any difficulty in determining the onset time in this way if the magnetotail were monitored continuously by a sufficiently dense network of space probes. Such, however, is not the case, and we usually have to deduce the overall structural change of the magnetotail from observations made at a single point, or, even in most favourable circumstances, two or three points at a time. This limitation of a practical nature has made the definition of the substorm onset in the magnetotail less clear-cut than it could in principle be.

The purpose of this paper is to review our past efforts to overcome this limitation and yield a coherent physical idea of the substorm onset in the magnetotail. Finding relatively rare occasions when more than one satellites were simultaneously orbiting in the magnetotail, or combining statistically the observations made at different occasions, we have been able to construct a reasonably consistent picture of what goes on in the magnetotail at the onset of the expansion phase and during a brief interval that precedes that onset.

These efforts notwithstanding, the limitation of the available information casts shadow on our current understanding. First, there still is a missing link in our phenomenology of the magnetotail substorm, because a certain region of the magnetotail which seems to have an utmost importance to the substorm physics has not

been explored. Second, while the analyses have been fairly well advanced for relatively large substorms and isolated events, much less is known about the physical nature of smaller substorms and continuous activity. We shall try to point out principal problem areas which remain to be pursued.

Since excellent review articles on magnetotail substorms were written only a few years ago (RUSSELL and MCPHERRON, 1973; RUSSELL, 1974), we shall avoid giving a full account of the subject and concentrate on major advances and controversies that have developed in more recent years.

2. In the Tail Lobe: Reduction in the Field Strength

Rapid decrease in the field magnitude in the tail lobe is one of the basic signatures of the magnetotail substorm (AUBRY and MCPHERRON, 1971). The start of this decrease is coincident, within a range of several minutes, with the appearance of an expansion-phase signature on the ground, namely with the earliest onset of a low-latitude positive bay (NISHIDA and NAGAYAMA, 1973; CAAN *et al.*, 1973). At the corresponding moment the tail diameter starts to decrease (MAEZAWA, 1975), and hence the flux content of the magnetotail is indeed reduced by the occurrence of a substorm.

The reduction in the tail flux content seems to occur over a wide longitudinal sector that probably encompasses the entire tail width, as the above correlation has been observed independently of the local time of the observing site in the tail lobe. Dual satellite observations like Fig. 1 supports this contention. The top panel of the figure shows the solar magnetospheric X -component records of two satellites which were separated longitudinally by $>20 R_E$. One of the satellites (AIMP-D, indicated in the figure as D) had a solar magnetospheric Y coordinate of $\sim -18 R_E$ and was very close to the tail magnetopause on the morning side. The middle panel shows magnetograms from low-latitude stations in the night sector, and the occurrence of at least two cases of low-latitude positive bays can be recognized. Vertical lines are drawn through the starting times of these positive bays. These were also the times when negative bays sharply began to intensify in the night sector of the auroral zone as shown in the bottom panel. Within several minutes of these times, decreases in the X -component of the lobe field started at both satellite positions.

Sometimes the decrease in the field strength in the tail lobe occurs repeatedly in close succession. The decreases indicated by second and third dashed lines in Fig. 2 represent such a case. It is seen in the top panel that the magnitude of the X -component recorded by both satellites had two closely spaced peaks, each of which corresponded to the onset of a low-latitude positive bay as seen in the middle panel. Thus a multiple onset of the expansion phase observed on the ground is associated with a stepwise release of energy from the magnetotail.

In the foregoing example of the double onset, $|X|$ -component of the lobe field resumed an increasing trend only several minutes after the first of the double onsets.

Fig. 1. Substorm observations in the tail lobe (top) and on the ground (middle and bottom). Satellite positions at the beginning and the end of the interval are given by solar magnetospheric coordinates.

This indicates that the process of the energy release which was initiated at the first onset was not efficient enough to dispose of the continuing addition of the flux to the tail. A full-fledged conversion of the stored energy took place after the second of the double onsets.

That the decrease in the lobe field strength is observed over a wide longitudinal range at the onset of the expansion phase does not necessarily mean that the energy conversion process operates in the plasma sheet with an equally wide longitudinal extent. Even when the collapse of the tail field lines occurs in some limited longitudinal sector, the decrease in the magnetic pressure initiated in that sector is communicated to other sectors of the tail by the rarefaction wave, and its effect is

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Fig. 2. Same as Fig. 1 (NISHIDA and NAGAYAMA, 1975).

expected to be observable everywhere in the tail lobe with a delay corresponding to the propagation time of the hydromagnetic wave of the fast mode.

3. In the Near-Earth Plasma Sheet: Resumption of Dipole-Like Field Configuration and Enhancement in Particle Flux

In the near-earth region of the magnetotail at the solar magnetospheric X coordinate of around $-10 R_E$, the rotation of the magnetic field vector is the characteristic feature observed during substorms. The rapid rotation toward the more dipolar direction occurs at the expansion-phase onset which is signified, among other things, by the onset of a low-latitude bay, and it is preceded by an interval of 0.5–1 hr in which the field lines become more extended (McPHERSON *et al.*, 1973).

Fig. 3. Substorm observations at the geosynchronous altitude by ATS-6. Upper four traces are magnetic field data, and lower four traces are proton data (WALKER *et al.*, 1976).

These features are frequently observed at the geosynchronous altitude, as shown by three examples in Fig. 3. The satellite was in the night sector, and three dashed lines indicate the beginning of abrupt increases in H (which is antiparallel to the earth's dipole axis) and decreases in $-V$ (which is directed approximately toward the earth) that correspond to the rotation to more dipolar configuration. These abrupt changes were preceded by gradual variations having an opposite sense and starting roughly 1 hr earlier (WALKER *et al.*, 1976). Figure 4 shows low-latitude ground magnetograms in the corresponding interval, and each dashed line can be seen to correspond to an onset of a low-latitude positive bay (S. Kokubun, private communication, 1977).

The records shown in the lower half of Fig. 3 are those of energetic protons. Each of the field rotations was accompanied by an enhancement of the proton flux; particularly in second and third events the flux increase was recorded in all energy channels and was preceded by a flux decrease. Since the energy of the observed protons is high enough to fall in the energy range of the trapped particles, the

Fig. 4. Low-latitude ground magnetograms corresponding to Fig. 3 (S. Kokubun, private communication, 1977).

decrease-increase sequence of the proton flux was attributed primarily to the earthward and then tailward shift of the trapping boundary that results from the change in the magnetic field configuration (BOGOTT and MOZER, 1973), but the anisotropy measurements of these protons indicate that the rapid flux increases are frequently associated with earthward motion, presumably from the plasma sheet (WALKER *et al.*, 1976).

The earthward injection of particles is more evident at lower energies where the trapped population is absent. Namely, at energies ≤ 10 keV, sharp and conspicuous enhancements in proton and electron fluxes are observed in the near-midnight sector of the geosynchronous orbit within 10 min of the appearance of the expansion phase signatures on the ground (e.g., KAMIDE and McILWAIN, 1974). An example is shown in Fig. 5. In this figure the left-hand column displays electron fluxes at 0.7–1.9 (EA), 1.8–5.4 (EB), 5.9–17.8 (EC) and 17–53 keV (ED), and the central column shows proton fluxes at >5 (PA), >15 (PB) and >38 keV (PC). Expansion-phase onset times defined by the low-latitude positive bay on the ground (right-hand column, middle panel) are indicated by dashed lines in each column. The enhancement of the flux was observed in every channel at each onset of the

Fig. 5. Substorm observations at the geosynchronous altitude by ATS-5. Left and middle columns show particle data, and right-hand column shows, from the top, magnetic field observed by ATS-5, ground magnetic field data obtained at a pair of low-latitude and a pair of auroral-zone stations, and the inclination θ of the interplanetary magnetic field with respect to the solar magnetospheric equatorial plane (FUJII *et al.*, 1975). Shadings indicate the interval when ATS-5 was in earth's shadow.

expansion phase. This indicates that the inner boundary of the plasma sheet rapidly moved inward.

Sometimes the flux enhancement of these low energy particles is also preceded by an interval of a depressed flux. In Fig. 5 it is seen that in low-energy channels like EA, EB, EC and PA particle fluxes started to drop sharply about 1–2 hr before the flux enhancement at the second expansion-phase onset in the figure. A possible reason for such a depression is the thinning of the plasma sheet; namely, the plasma sheet which had penetrated to the geosynchronous altitude in consequence of the preceding substorm activities briefly reduced its thickness before the onset of the subsequent expansion phase (FUJII *et al.*, 1975; ROSTOKER *et al.*, 1975).

Indications of the plasma sheet thinning before the expansion-phase onset have been obtained also by particle measurements made at slightly larger distance by OGO 5 (KIVELSON *et al.*, 1973). Although energies of the observed particles are rather high (~ 80 keV for electrons and ~ 100 keV for protons), at distances of $\geq 10 R_E$ from the earth these particles may be considered to comprise high energy tail of the plasma sheet population. The left panel of Fig. 6 shows the time difference

Fig. 6. Dependence of thinning onset and recovery times (relative to the expansion-phase onset time) on the distance $(X^2 + Y^2)^{1/2}$ (NISHIDA and FUJII, 1976).

ΔT_D , defined as “the time when the flux started to decrease” minus “the onset time of the low-latitude positive bay,” versus the projection $(X^2 + Y^2)^{1/2}$ of the observing distance of the solar magnetospheric equatorial plane. (In order to exclude flux decreases that may be due to spatial effect a limit has been imposed on the distance ΔZ of the observing site from the tail midplane.) It is seen that $|\Delta T_D|$ differs from zero at $(X^2 + Y^2)^{1/2} \leq 15 R_E$ but at greater distances $|\Delta T_D|$ is nearly zero in most cases. In contrast, the right panel of Fig. 6 shows that ΔT_R , namely “the time of flux increase” minus “the onset time of the low-latitude positive bay,” is clustered around zero at $(X^2 + Y^2)^{1/2} \leq 15 R_E$ but is tens of minutes long at greater distances. Thus there seems to be a critical distance which separates the plasma sheet into two regions according to its behaviour during substorms; earthward of that distance the plasma sheet thins before, and recovers rapidly at, the expansion-phase onset, while away from that distance the plasma sheet starts to thin at the expansion-phase onset and recovers some tens of minutes after the onset (NISHIDA and FUJII, 1976; HONES *et al.*, 1973). The contrasting behaviours of the near-earth and the distant portions of the plasma sheet during substorms have been demonstrated also by a comparison of simultaneous observations of particle fluxes by OGO 5 and Vela 4A (PYTTE *et al.*, 1976).

4. In the Distant Plasma Sheet: Southward Turning of the Field and Decrease in the Sheet Thickness

The thinning of the plasma sheet at $(X^2 + Y^2)^{1/2} \sim 17 R_E$ is one of the most thoroughly documented signatures of the expansion-phase onset. At that distance the decrease in particle flux usually begins with an onset of the expansion phase of the auroral substorm (AKASOFU *et al.*, 1971a), although in some occasions the thinning has been found to precede the expansion-phase onset (HONES *et al.*, 1971). Inside the thinned plasma sheet, plasma flows tailward with a velocity of several hundred km/sec

Fig. 7. Substorm observations in the distant plasma sheet (first two panels) and simultaneous ground magnetic records.

(HONES *et al.*, 1974). In addition, an impulsive burst of hard electrons sometimes occurs at the onset of the expansion phase and lasts for a few tens of minutes (AKASOFU *et al.*, 1971b). Unfortunately the Vela series of satellites were not instrumented with magnetometers, but other satellites orbiting the distant tail at $|X| \gg 15 R_E$ have observed a reversal in the north-south component B_z of the low-latitude tail field; a few minutes after the onset of the expansion phase on the ground, B_z turns from northward to southward (NISHIDA and NAGAYAMA, 1973). Recall that in the corresponding interval the same component of the field is directed northward and increases sharply at $|X| \sim 7 R_E$ (Figs. 3 and 5).

A relatively well documented example showing the foregoing features is given in Figs. 7 and 8. The top panel of Fig. 7 shows the solar magnetospheric northward

Fig. 8. Energetic electron and magnetic field data associated with observations presented in Fig. 7 (BAKER and STONE, 1977).

component of the magnetic field and the plasma flow velocity observed at the radial distance of $\sim 35 R_E$ in low latitude (at θ_{SM} of several degrees) near the midnight meridian. The bottom panels display ground magnetograms, and expansion-phase onset times determined by low-latitude positive bay and/or Pi 2 burst are indicated by vertical lines. Figure 8 is the energetic electron data in the corresponding interval; the top panel shows fluxes of ≥ 200 keV and ≥ 1 MeV electrons, the second panel the spectral exponent γ , the third panel the amplitude S of the first harmonic of the azimuthal variation, and the fourth panel the amplitude K of the second harmonic. The remaining three panels are magnetic field data (FRANK *et al.*, 1976; BAKER and STONE, 1977; HONES, 1978).

Let us look at the third onset first. There occurred at this time, or shortly (≤ 10 min) after this, southward turning of B_z , anti-earthward flow of plasma, and

enhancement of ≥ 200 keV electron flux. These energetic electrons also started to stream tailward shortly after the enhancement.

The earlier two onsets seem to constitute a double onset event. The first of these caused little perturbation at satellite's position except for the occurrence of a very energetic ($E \geq 1$ MeV) electron burst about 10 min later. The second of these, however, caused all the characteristic signatures with a delay of about 10 min. The enhancement of the anisotropy amplitude S is particularly noteworthy in this case.

Although not included in the present example, intense bursts of energetic protons ($E \sim 50$ – 200 keV) have also been observed in the low-latitude magnetotail at $|X| \sim 35 R_E$. The occurrence of these proton bursts is limited to the dusk sector of the tail, while energetic electron bursts do not show dawn-dusk asymmetry in their occurrences. The onset of the bursts is coincident (within a possible range of several minutes) with the earliest onset of the low-latitude positive bay on the ground (TERASAWA and NISHIDA, 1976; ROELOF *et al.*, 1976).

5. The Neutral Line Model

A phenomenological model which is essentially consistent with foregoing observations is shown in Fig. 9. In this model the formation of an X -type neutral line is assumed at the distance of $|X| \sim 15 R_E$ (third panel). Tailward of the neutral line B_z is directed southward and plasma moves tailward. Energetic particles produced at the neutral line fill the magnetic loop shown dotted in the figure. On the earthward side field lines resume more dipolar configuration, plasma sheet expands and its inner boundary moves earthward. The model has been developed by several groups by putting various pieces of evidences together (e.g., RUSSELL and MCPHERRON, 1973; HOFFMAN and BURCH, 1973; HONES *et al.*, 1973; TERASAWA and NISHIDA, 1976; HONES, 1976).

On the anti-earthward side of the neutral line the field line structure that is deduced from magnetic field observations is convex toward the neutral line as illustrated in Fig. 10. This structure implies that the plasma flow in the boundary region of the plasma sheet is directed nearly parallel (or, antiparallel) to the magnetic field. This can be seen as follows. The uniformity of the electric field requires that $V_N^{(E)} B_N = V^{(E)} B$, where $V^{(E)}$ denotes the velocity component perpendicular to the magnetic field; the right-hand side is evaluated at an arbitrary point P on the field line passing the tail midplane at point N. The observed field structure implies $B_N < B$, and for the convex field structure to be maintained for a sufficiently long distance from the neutral line the component V of the velocity parallel to the midplane should satisfy $V \geq V_N = V_N^{(E)}$. This means that V is due largely to the field-aligned component of the velocity rather than to $V^{(E)}$, since $V^{(E)} = (B_N/B) V_N^{(E)} < V_N^{(E)}$. The observed flow velocities indeed seem to have a substantial component parallel to the field orientation (HONES *et al.*, 1974, 1976).

The field-aligned, anti-earthward flow of plasma can be an intrinsic part of the magnetotail deformation that drives reconnection in the near-earth region of the

Fig. 9. Sequence of magnetotail transfiguration during a substorm. Formation of the neutral line (between panels B and C) corresponds to the onset of the expansion phase.

Fig. 10. Field configuration near the neutral line.

magnetotail. As pointed out by CORONITI and KENNEL (1972), erosion of the dayside magnetosphere and flux pile-up in the magnetotail produces steep inclination in the magnetotail attitude (with respect to the incidence direction of the solar wind) in the transition region between the dayside magnetosphere and the magnetotail. The enhanced pressure of the solar wind applied to this region of the magnetopause induces motion inside the magnetosphere. Reconnection is caused as field lines in northern and southern halves of the tail are pushed toward each other by this pressure. In addition, the pressure produces field-aligned, anti-earthward flow as it acts to push plasma tailward.

The field-aligned flow of similar nature is involved in analytic models of the reconnection produced by Sonnerup or Yeh and Axford (see review by VASYLIUNAS (1975)). The boundary condition which specifies models of this type is that of the cornered flow, and the colliding streams directed toward the interface are deflected at the slow expansion fan where the field-aligned, issuing component is produced in the flow velocity. The presence of this component in the boundary region of the plasma sheet has been predicted also by a numerical model of the reconnection where the compressibility is taken into account (HAYASHI and SATO, 1977). In the compressible model the expansion of the heated plasma seems to intensify the field-aligned issuing flow.

6. Discussion

Before the neutral line model can be established as a proper explanation of the substorm expansion phase, however, it would be essential that the presence of the neutral line be confirmed by in-situ observations. This has not been possible so far, because few satellites have traversed the tail midplane at the distance of $\sim 15 R_E$ where the neutral line is likely to be formed. The task remains as one of the most urgent missions of the magnetospheric study today.

Nevertheless it can be said that a number of case studies carried out in the past is consistent with the idea that the neutral line is formed in the near-earth portion of the tail at the onset of the substorm expansion phase. Typical examples are second and third expansion phases of Figs. 7 and 8. The first event, however, is an exception, and an explanation is needed why neither the southward B_z nor the anti-earthward plasma flow were observed in that case. The simplest possible way is to assume that the length of the neutral line was quite limited longitudinally at that time and did not reach the near-midnight meridian where the satellite was located (Fig. 11, top). The weakening of the cross-tail current might have occurred in that meridian too but probably it was not severe enough to produce the neutral line. Alternatively it may be considered that the neutral line extended to that meridian but the reconnection stopped to operate after a short while and consequently the field line loop produced thereby was too small to produce a southward B_z at the satellite position (at $|X| \sim 35 R_E$) (Fig. 11, middle). Strong earthward flow of plasma

Fig. 11. Top: Two conceivable models of multiple expansion phase onset. The first possibility is the stepwise extension of the neutral line length (above), and the second possibility is the stepwise enlargement of the field line loop (below). Bottom: Model of successive but separate expansion phase onsets. N means neutral line.

from distant magnetotail could be suggested as a possible cause of the suppression of the near-tail reconnection.

The second event which closely followed the first event is likely to have occurred when the weakening of the near-earth portion of the tail current developed further. The multiple onset of the expansion phase probably corresponds to a successive, fuller development of the current weakening and/or the neutral line length (Fig. 11, right).

Conversely, the statement made in the preceding paragraph could be taken as a definition of the "multiple onset" of an expansion phase. Namely, if the region of the weakened cross-tail current increases its longitudinal and/or radial extent in discrete steps and hence the length of the neutral line and/or the dimension of the field line loop are increased in discrete steps, each step can be considered to define multiple onsets of a single expansion phase. When on the other hand neutral lines are formed one after another and are carried successively away to greater distances from the earth (Fig. 11, bottom), it may be more appropriate to regard each neutral-line formation as signifying the onset of a separate expansion phase. In broader terms, one could call a set of expansion-phase onset signatures as multiple onsets if the same physical process continued and merely increased its intensity and/or scale at each step, while the signatures may better be regarded to represent a series of separate events if a new process is initiated at each step following the decay or departure of the earlier process. This definition appears logical, but practically it would be difficult to identify individual multiple onset events conforming to this

definition unless field and plasma characteristics in the near-earth portion of the plasma sheet are monitored. (In fact we have used the term multiple onset so far rather loosely without referring to the above definition.)

It has been known that the onset of the low-latitude positive bay on the ground is not globally simultaneous and varies slightly with local time. It is tempting to consider that this feature is the reflection of the successive, longitudinal extension of the neutral line. But comparisons between low-latitude ground observations and low-latitude tail observations at $|X| \gtrsim 17 R_E$ have not yet confirmed such a simple relationship. Rather, comparisons of simultaneous ground and satellite data have shown that the neutral line signature (namely the southward turning of B_z) observed at any local time tends to be most closely associated with the ground signature observed in the premidnight sector (where the bays tend to show earliest appearance) (NISHIDA and HONES, 1974). More extensive survey is needed to disclose the magnetotail counterpart of the local-time dependent occurrence pattern of low-latitude positive bays. The region of importance would again be the low-latitude magnetotail at the distance of $\sim 15 R_E$.

If the neutral line extends longitudinally in discrete steps, the earthward injection of plasma is expected to occur from broader local-time sector with the development of the neutral line. Such an indication, however, has not yet been reported. The reason may be that most of available data on the injection was obtained at the geosynchronous altitude which is probably too far from the neutral line to detect the detailed structural change of the neutral line.

In the foregoing model the neutral line was supposed to be formed at $|X| \sim 15 R_E$. Suggestions have been made that the location of the neutral line is sometimes much further than this. In one of such instances, a prolonged presence of a neutral line beyond $|X| \sim 17 R_E$ was inferred from a rapid earthward flow of plasma that lasted for almost 10 hr. This interval of earthward flow roughly coincided with an equally prolonged interval of moderately strong geomagnetic activity, but no detailed correlation between individual signatures was said to be recognizable (HONES *et al.*, 1976). Since in the open model of the magnetosphere a neutral line is thought to be permanently present in the distant tail, the above might better be described as an enhancement of the reconnection rate at that distant neutral line. It is not clear, however, why a moderately strong geomagnetic activity, which is presumably associated with a rather expanded auroral oval, is associated with a neutral line located at a large distance. Actually it does not seem to have been established by ground observations that a prolonged activity can be interpreted in terms of a succession of the expansion-phase to recovery-phase sequence of a typical substorm. Hence it is not obvious that the magnetotail process in a prolonged active interval is basically the same as that associated with substorms. Although it would not be correct to say that prolonged activities and substorms are driven by entirely different processes, possibility exists that the principal driving mechanisms for these two types of disturbances are not fully identical. Possible alternative processes include coupling of the DP2 (i.e., IMF driven) electric field with enhanced ionospheric conductivity.

Emphasizing this possibility, Pytte *et al.* (1978) have designated the prolonged geomagnetic activity as "convection bay."

Association with a distant neutral line has been suggested also for small substorms that tend to occur when the auroral oval is contracted. Topologically this association seems to be more plausible than that for prolonged activities, but few detailed case studies seem to have been conducted so far to establish this idea.

As an alternative interpretation of the available information, LUI *et al.* (1977) have proposed that the southward B_z represents a passage of the thinning wave propagating tailward. In their picture the thinning wave has a crest of $\sim 10 R_E$ width where field lines are more sharply inclined, and this spatially confined feature is suggested to be the nature of the southward B_z observed during the expansion phase. Observationally, however, the southward B_z has been detected from $|X| \sim 25 R_E$ to beyond $\sim 60 R_E$ with a duration of as long as 0.5–1 hr, and apparently it does not represent a spatially confined structure as they suggest.

In addition, it was supposed by LUI *et al.* (1977) that the plasma sheet thinning begins everywhere at or after the onset of the expansion phase. This is contrary to the observation that the thinning starts earlier than that onset in the near-earth region of the plasma sheet. The precursory thinning of the plasma sheet has an important bearing on the initiation of the expansion phase, because the ion tearing mode instability is expected to arise and disrupt the cross-tail current when the thickness is reduced to some threshold value (SCHINDLER, 1974). It is important to observationally fix the threshold level when more data from the near-earth region of the plasma sheet become available.

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