The Interplanetary Magnetic Field B_y Effects on Large-Scale Field-Aligned Currents Near Local Noon: Contributions From Cusp Part and Noncusp Part

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The effect of the interplanetary magnetic field (IMF) B_y component on the distribution of dayside large-scale field-aligned currents (FACs) is modeled. The study is done by dividing these FACs into a cusp part and a noncusp part according to the coexisting plasma. We propose that the location of the cusp part FACs shifts in the longitudinal direction whereas the location of the noncusp part FACs shifts in both longitudinal and latitudinal directions in response to the IMF B_y. If combined, the noncusp part region 1 FAC can be found poleward of the cusp part FAC systems when the IMF B_y is strong. Since these two FACs (the cusp region FAC and the poleward-leaped region 1 FAC) flow in the same direction poleward of the cusp, they reinforce each other in building a strong FAC which is called DPY-FAC. The strong IMF B_y effect on the dayside FACs near local noon is thus explained by this model. Another important result is that the polewardmost part of the DPY-FAC (or NBZ current under strong IMF B_y) flows on closed field lines even though it is located where the polar cap conventionally exists. Relative distortions of noncusp part FAC compared to the polar cap size are expected to be less significant when the IMF is southward as compared to IMF northward, yet the distortion itself is expected even for southward IMF as long as $|B_y| > |B_z|$. The present model is supported by Viking particle and magnetic field data.

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1. INTRODUCTION

There exist several different field-aligned currents (FACs) in the dayside: the dayside region 1 and region 2 FACs [*Zmuda and Armstrong*, 1974; *Iijima and Potemra*, 1976a; *McDiarmid et al.*, 1978], the cusp region (0) FAC [*Maezawa*, 1976; *Iijima and Potemra*, 1976b], the region 0 FAC [*Heikkila*, 1984; *Bythrow et al.*, 1987], and (the polar cap part) NBZ current [*Iijima et al.*, 1984]. The first four of these five FAC systems exist permanently for any interplanetary magnetic field (IMF) directions.

Unfortunately, there is some confusion about the terminology. First, the term region 1 FAC is often used without any distinction between the cusp part and the other dayside part. This distinction is essentially impossible by means only of ionospheric convection measurements [e.g., *Heppner and Maynard*, 1987] or even of satellite magnetic field observations [e.g., *Iijima and Potemra*, 1976*a*] unless combined with other high spatial resolution data that can provide information on the location of the cusp. Only recently have simultaneous particle and magnetic field measurements with high spatial resolution been achieved, so that the FAC can be subdivided on the basis of coexisting particle populations. It is now evident that the coexisting particle populations for the dayside region 1 FAC differ considerably between the cusp part and the noncusp part. Near local noon, the region 1 FAC is mostly copopulated with cusp particles [*Erlandson et al.*, 1988], while the other dayside region 1 FAC is copopulated with low-latitude boundary layer (LLBL) type particles [*Potemra et al.*, 1987]. These results are more strict evidence of what *McDiarmid et al.* [1979] already suggested from ISIS 2 measurement.

The distinction between the cusp part and the noncusp part indicates that the magnetospheric source regions for these FACs are different. Therefore it is better to distinguish them by different names, e.g., cusp part FACs and noncusp part dayside FACs, based on the coexisting particles.

We call a dayside region 1 FAC a cusp part FAC if the coexisting plasma population is dominated by the magnetosheath particles. Large-scale FACs found in the cusp proper, the boundary cusp, or in the mantle cusp [*Kremser and Lundin*, 1990] fall into this category. That means the cusp region (0) FAC also belongs to this category. A noncusp part dayside FAC coexists predominantly with magnetospheric particles including some magnetosheath plasma. Large-scale FACs found in the LLBL, in the lobes, or in the plasma sheet are classified as the noncusp part.

The other problem is that we have many different names for the same FAC systems. For example, the cusp region FAC is sometimes called (cusp part) region 0, poleward part cusp region, traditional cusp, region 3, mantle [*Bythrow et al.*, 1988], and (the cusp part) NBZ FACs. All these are the same current system except that some names are used for northward IMF conditions, some for southward, and the others are used for both northward and southward IMF conditions. In order to avoid the terminology confusion, we use cusp-0 for the cusp part region 0 (the cusp region) and cusp-1 for the cusp part region 1. The terms region 1 and region 0 are used for the noncusp part dayside region 1 or region 0 FACs (see Figure 1*a* for the usage of the terminology in this paper).

The IMF B_z component is well known to control the intensity and the latitudinal location of large-scale FACs in the dayside as well as in the nightside [e.g., *Levitin et al.*, 1982; *Araki et al.*, 1984]. Similarly, the IMF B_y component is well known to cause the DPY disturbances near the local noon area [*Friis-Christensen and Wilhjelm*, 1975]. The related FACs, which are sometimes called the DPY-FACs, are located approximately where the cusp-1 and cusp-0 FACs normally exist except that the poleward part of the DPY-FACs extends further toward the polar cap, as shown in Figure 1*b* [*Iijima and Potemra*, 1976*b*; *McDiarmid et al.*, 1978; *Wilhjelm et al.*, 1978; *Friis-Christensen et al.*, 1985; *Erlandson et al.*, 1988]. This is why the poleward DPY-FAC is included into the NBZ current [*Iijima and Shibaji*, 1987]. The intensity of the DPY-FACs is stronger than those of any other dayside FACs [*Yamauchi and Araki*, 1989]. Morphologically, the formation of the DPY-FACs is so far attributed to the longitudinal shift of the demarcation line between the prenoon and postnoon sides of the cusp part (cusp-1 and cusp-0) FACs as shown in Figure 2*a*. However, there are two reasons that we may not be satisfied with this explanation alone.

The first problem is their intensities. *Friis-Christensen et al.* [1985, Figure 8] showed that the DPY-FACs are stronger than the ordinary cusp-1 and cusp-0 FACs without B_y effect. This ground-based result is also supported by Magsat observations [*Araki et al.*, 1984; *Iijima and Shibaji*, 1987; *Yamauchi and Araki*, 1989] for the poleward part DPY-FAC. A simple shift of the demarcation line may not explain such strong current intensities. The second problem is the behavior of the noncusp part dayside FACs. The cusp part FACs and the noncusp part FACs are independent each other in the sense that their source regions are quite different. The IMF B_y is expected to influence not only the locations of these source regions but also the mapping relations between the source regions and the ionosphere because the geomagnetic field configuration is distorted by the IMF B_y too. We may reasonably expect quite different IMF dependencies between these two types of FACs. If so, we may not ignore the possibility that the noncusp part FACs take part in constructing the DPY-FACs.

For these points, we may set questions in the following way. How does the IMF B_y control the cusp part and noncusp part FACs, respectively? How are the DPY-FACs composed? The last question is directly related to the identification of the source of the NBZ current when the IMF B_y is strong. For southward IMF conditions, quasi-steady state reconnection models [e.g., *Crooker*, 1988; *Cowley et al.*, 1991; *Saunders*, 1992] or flux transfer event models [e.g., *Smith and Lockwood*, 1990] may account for some of the problems raised here for both the cusp part and the noncusp part FACs. However in this paper, we take a different approach, namely, a morphological approach which can be directly examined by simultaneous, high-resolution plasma and magnetic field observations.

2. MODEL

Let us discuss what is implied from the consideration of the current source region. If the solar wind energy is somehow converted to the electromagnetic energy in the cusp entry layer or the exterior cusp where the solar wind is directly decelerated [*Haerendel et al.*, 1978; *Lundin*, 1985], any FAC systems generated due to this mechanism must originate where the solar wind plasma injects and hence must be copopulated with cusp particles. The IMF B_y effect on such a FAC system is expected to appear as a shift of its location, which must synchronize with the cusp position, i.e., in the longitudinal direction but not in the latitudinal direction. We may reasonably apply this result to the cusp part (cusp-1 and cusp-0) FACs, as many authors have concluded from satellite data [e.g., *Erlandson et al.*, 1988]. The demarcation line between prenoon side and postnoon side FACs is thus expected to shift only in the longitudinal direction as shown in Figure $2a$ depending on the IMF B_y polarity.

One might argue that the FACs copopulated with mainly the cusp particles are not necessarily generated where the cusp particles are generated; however, in this paper we assume that the cusp-0 and cusp-1 FACs in the cusp proper and the mantle cusp are generated from where the cusp particles originate, i.e., at the entry layer or the exterior cusp. We should also note here that the above considerations are applicable for both northward IMF and southward IMF, respectively, although the particle features of the cusp are quite different between northward IMF and southward IMF. Readers may find that the following discussion for the noncusp part FAC is also applicable for both northward IMF and southward IMF, respectively.

The noncusp part dayside FACs come from a somewhat longer distance, e.g., LLBL, lobes or even plasma sheet. That means we have to also consider the mapping relation between the ionosphere and the magnetosphere along the geomagnetic field because the geomagnetic field is distorted by the IMF B_y component. The situation is different from the cusp part: the geomagnetic field distortion is not as an important effect as the distortion of the source location in determining the distribution of the cusp part FACs. We thus expect a quite different response to the IMF B_y between the cusp part FACs and the noncusp part FACs. How do the noncusp part FACs respond to the IMF B_y?

There is a clue to consider their response. The dayside polar arc sometimes appears poleward of the cusp. When the IMF B_y is strong, it is distorted such that we may find the polar arc either in the morning sector or in the afternoon sector depending on the IMF B_y polarity [*Elphinstone et al.*, 1990]. The region between the polar arc and the ordinary auroral oval (morning or evening oval) is filled with precipitating particles whose characteristics are similar to those found in the region 1 FAC regime [*Frank et al.*, 1986; *Eliasson et al.*, 1987]. This elucidates the poleward leap of the region 1 FAC [*Jankowska et al.*, 1990] or, more generally, the latitudinal shift as well as the longitudinal shift of the noncusp part FACs as shown in Figure 2*b*. The direction of this longitudinal shift of the region 1 FAC is opposite to that of the cusp location. The noncusp part region 0 FAC, which is much less intense in magnitude than the region 1 and region 2 FACs, is ignored in Figure 2.

These UV observations of distorted polar caps are made for northward IMF, and Figure 2*b* could be valid only for northward IMF. However, the above discussion, i.e., that the location of the noncusp part may be distorted in the manner of Figure 2*b*, is still valid to some extent for southward IMF conditions. According to the Magsat observations [*Iijima and Shibaji*, 1987; *Yamauchi and Araki*, 1989], there is no qualitative difference in the FAC distributions between IMF northward and southward conditions if $|B_y| > |B_z|$. We here expect that the distribution of the noncusp part FAC is still distorted, to some degree, as shown in Figure 2*b* even when the IMF is southward as long as $|B_y| > |B_z|$. Since the polar cap expands while the polar arc shrinks for

IMF southward conditions, relative distortion of the noncusp part FAC compared to the polar cap size is expected to be less significant when the IMF is southward than when the IMF is northward, yet the distortion itself is expected even for southward IMF as long as $|B_y| > |B_z|$.

Thus the distributions of cusp part FACs and noncusp part dayside FACs are to be modified in different manners by the IMF B_y component. If one combines these two types of FACs, one may construct an unified picture of FAC distribution near local noon as shown in Figures $2c$ and $2d$ when the IMF B_y is strong. The duskside region 1 FAC, e.g., for $B_y > 0$ cases, leaps poleward of the cusp part FACs, reinforcing the prenoon part cusp-0 FAC in constructing the poleward *DPY*-FAC. This picture agrees with the results by *McDiarmid et al.* [1979] in which the cusp-0 FAC is smoothly connected, e.g., for $B_y > 0$ cases, to the duskside region 1 FAC as is indicated in their summary diagram Figure 9. The cusp-1 FAC is no longer located at the noonward extended position of the region 1 FAC, as is traditionally assumed (see Figure $1a$). The strong control by the IMF B_y is thus easily explained. This possibility has been ignored in the traditional picture of Figure $1a$.

The model also answers where the NBZ current comes from when the IMF B_y is strong [*Iijima and Shibaji*, 1987]. The cusp part NBZ current is the same as the cusp-0 FAC as is mentioned in the introduction, and its source is associated with cusp entry layer. The polar cap part of NBZ current could be the poleward-leaped region 1 FAC which flows on closed field lines, not on open field lines. The poleward limit of this FAC is the dayside polar arc. Note that this is for the strong IMF B_y case. The situation for purely northward IMF could be different.

Since there were no high time resolution particle data taken simultaneously with the magnetic field data in the past study, we could not see if the detected large-scale FAC is on closed field lines or open field lines. Under this circumstance, a large-scale FAC found at very high latitude was thought to be on open field lines. However as mentioned above, a polar cap FAC can be on closed field lines if it is the poleward-leaped region 1 FAC. In order to see it, we need to compare simultaneous particle and magnetic field data with high temporal and spatial resolution. The rest of this paper is devoted to supporting the present model by showing some satellite observations of the poleward-leaped region 1 FAC when IMF B_y is strong. We will first examine IMF northward conditions; then we will study IMF southward conditions. We use Viking magnetic field and particle data for this purpose and subdivide the large-scale field-aligned current according to the coexisting plasma populations.

3. Observation

From the Viking cusp orbits, we select periods when the IMF B_y is relatively large and the Viking pass is nearly along the meridian plane. FACs are determined from Viking magnetic field data, while Viking particle data give us the information of the satellite location in terms of the cusp part, noncusp part, and the polar cap. The particle data are also used to support the IMF B_z direction [*Woch and Lundin*, 1992] in addition to the direct IMF measurement by IMP 8 satellite.

Figure 3 (orbit 871) shows an example of cusp traverse for the northward IMF case as is seen from its ion dispersion, i.e., increasing characteristic energy toward higher latitude (from left to right in the figure). The IMF observed by IMP 8 is $B_y = -3$ nT and $B_z = +6$ nT, and AE is around 300 nT.

We first examine the particle data. The ion energy-time spectrogram shows the V-shaped structure for 0532-0546 UT with acceleration feature (e.g., elevated ion conics) at its poleward part (0541-0545 UT). The electron energy-time spectrogram shows intense 100-300 eV electron population for the same period. Thus this region (0532-0546 UT) is filled with the directly entered magnetosheath plasma. Any FACs on 0532-0546 UT are classified as the cusp part in the present definition.

There are structured keV electrons and upward ion beams poleward of the cusp part (0546-0550 UT). Especially after 0547 UT, there is no directly entered ion or directly entered electron, indicating that it is the noncusp part as of the present definition. These particle features are commonly found in both dayside region 1 FACs and polar arcs. The Viking UV images of this orbit (R. Elphinstone, private communication, 1991) indicate that it is the dayside polar arc of either the expanded boundary plasma sheet (for general cases, see, for example, *Jankowska et al.* [1990]) or the expanded LLBL. No matter which is the interpretation, this portion corresponds to the expanded (noncusp part) region 1 FAC. This arc is observed continuously for more than 1 hour (R. Elphinstone, private communication, 1992).

The magnetic field data (gradient of the east component of the magnetic field B_E) indicate an upward large-scale FAC for 0535-0541 UT and a downward large-scale FAC for 0545-0550 UT. Small-scale fluctuations prevail over the large-scale FACs where the acceleration features are found (0541-0545 UT). This region is called as acceleration region of the boundary cusp [*Woch and Lundin*, 1992] and is often accompanied by such intense fluctuations. Therefore we may not simply use this part of the magnetic field data in order to obtain the large-scale FACs in the present study. The maximum ΔB_E deviation of 100 nT for the large-scale part (eliminating 0541-0545 UT) is still relatively large compared to the other Viking cusp observations.

The polarity of the FACs, i.e., upward on the equatorward side and downward on the poleward side in the morning sector, indicates that they are typical DPY-FACs for IMF $B_y < 0$. Here we are interested in the downward FAC for 0547-0550 UT, which is already identified as the polar arc, i.e., the noncusp part. Both the FAC and the polar arc terminate at 0550 UT, beyond which we may finally call the polar cap.

We have two important conclusions directly derived from this observation. First, there is a noncusp part FAC located poleward of the cusp contributing to the poleward part DPY-FAC, at least when the IMF is northward. Note that this FAC is also called the NBZ current [*Yamauchi and Araki*, 1989; *Iijima and Shibaji*, 1987]. Second, this noncusp part FAC flows on the polar arc, not on the polar cap. Thus the poleward part of the *DPY*-FAC, i.e., the NBZ current in *Iijima and Shibaji*'s [1987] definition, is flowing on closed field lines instead of open field lines. Since the arc is the poleward-extended morning oval, the FAC on that arc is interpreted as the poleward-expanded region 1 FAC. Its flowing direction (downward for 0547-0550 UT) agrees with that of the morningside region 1 FAC. On the whole, these results are consistent with the model of Figure 2*d* for dawnward IMF ($B_y < 0$).

A question may be raised whether or not this is a steady state feature. On the basis of satellite data alone, this question is difficult to answer; however, the main point of this present paper (deformed location of the noncusp part FAC) is still valid. In fact, the poleward leap of the noncusp part region 1 FAC is found in many other Viking traverses according to the comparison between the particle data and the magnetic field data. Among 32 possible orbits in which we may expect such a deformation of FAC distribution during northward IMF (we examined from July 17, 1986, to September 30, 1986), 18 passes show the poleward-leaped noncusp part FAC while six passes do not. The rest (eight passes) are unclear cases with rather short polar arcs and are difficult to distinguish from other phenomena like cusp poleward edges [*Yamauchi and Lundin*, 1993].

The poleward leap of the noncusp part region 1 FAC is sometimes observed for southward IMF too, as long as the IMF B_y is strong. One such example (orbit 1038) is shown in Figure 4.

The IMF condition is $B_z = -2$ nT and $B_y = +3$ nT, and *AE* is around 600 nT. This orbit, which is nearly along the 12 MLT meridian plane, does not cut through the cusp proper but only the boundary cusp. The cusp proper is considered to have shifted toward afternoon sector. The V-shaped ion distribution for 1338-1346 UT indicates that it is the cusp part as of the present definition. The electron data show that it is divided into the acceleration region of the boundary cusp (1338-1342 UT) and the accelerated mantle cusp (1342-1347 UT). A polar arc is recognized beyond them for 1347-1357 UT. Unfortunately, there is no UV image available; however, the intense bidirectional electrons with upward ion beams are clear indications that it is a typical arc.

The magnetic field data show a pair of large-scale FACs, a downward FAC on the equatorward side (1338-1342 UT) and an upward FAC on the poleward side (1342-1353 UT). These are typical DPY-FACs for duskward IMF ($B_y > 0$). Fortunately, they prevail over the small-scale fluctuation even on the acceleration region. Combined with the particle data, these large-scale FACs are easily divided into three parts: a cusp part downward FAC (1338-1342 UT), a cusp part upward FAC (1342-1347 UT), and a noncusp part upward FAC (1347-1353 UT). Two cusp part FACs are the extended prenoon part cusp-1 and cusp-0 FACs, respectively, as is expected from the duskward IMF condition (see Figure 2a). The noncusp part upward FAC is flowing within the polar arc which is considered to be the poleward-expanded afternoon arc driven by the duskward IMF ($B_y > 0$). On the whole, these results are consistent with the model of Figure 2c for duskward IMF ($B_y > 0$). Note that the noncusp part FAC is still classified as the NBZ current by *Iijima and Shibaji* [1987] because IMF $|B_y| > |B_z|$. Therefore we reach exactly the same conclusion as the previous case.

The statistics for the southward IMF are not as good as those of northward IMF. Among 18 possible orbits in which we may expect such a deformation of FAC distribution during southward IMF, eight passes show the poleward-leaped noncusp part FAC while eight passes do not. As mentioned in the previous section, we expect that the distortion of the noncusp part FACs by the IMF B_y component is less significant when the IMF is southward than when the IMF is northward. In other words, the leaped region 1 FAC need not always cover an extended area poleward of the cusp. This explanation does not necessarily mean that we may not have well-expanded polar arcs; another solar wind parameter such as dynamic pressure may control the position of the polar arc and the size of the polar cap, and we may still observe the well-expanded polar arcs for southward IMF condition like Figure 4 sometimes. With these explanations, the statistics support the present model for IMF southward conditions too.

4. Concluding Remarks

We have modeled the formation of the *DPY*-FAC in terms of the cusp part and the noncusp part FACs as shown in Figure 2. The proposed FAC distribution has been supported by Viking cusp orbit data (Figures 3 and 4) by comparing the particle data and the magnetic field data. There is a noncusp part FAC located poleward of the cusp contributing to the poleward part *DPY*-FAC. This noncusp part FAC, which is also called the NBZ current according to *Iijima and Shibaji*'s [1987] definition (including southward IMF as long as $|B_y| > |B_z|$), is flowing on the polar arc and is interpreted as the poleward-expanded region 1 FAC. Thus the region 1 FAC leaps poleward enforcing the cusp-0 FAC to construct the poleward part of the *DPY*-FACs under strong IMF B_y conditions. The enforced B_y effect by the cusp-0 and region 1 FACs might explain high intensity of the poleward part of *DPY*-FACs. This phenomenon is observed for both northward and southward IMF conditions, and the statistics strongly support the presented model for northward IMF conditions while they are at least consistent with the presented model for the southward IMF cases. Further study is necessary to clarify the case of southward IMF conditions.

According to the present result, pictures by *Iijima and Potemra* [1976*b*] and by *McDiarmid et al.* [1979] are not inconsistent. The result also explains the source of the polar cap part NBZ current at least when the IMF B_y is strong. It is flowing on closed field lines of the polar arc instead of on open field lines of the polar cap.

Let us mention the response time of the *DPY*-FACs to the changes of the IMF B_y. It must be different for the cusp part and for the noncusp part. The cusp part is known to show a quick response to the IMF changes [e.g., *Clauer and Banks*, 1986], while the region 1 FAC most likely does not. Therefore the model predicts that there must be at least two time scales for the *DPY*-FAC system in responding to the IMF changes. Such different time scales are observed by Magsat [*Yamauchi and Araki*, 1989], supporting the present model in this respect too.

The IMF B_z is also expected to move the positions of the cusp [*Carbary and Meng*, 1986] and the dayside FAC systems [*Levitin et al.*, 1982] in the latitudinal direction. It is likely that the degree of this shift is different between the morningside FACs (Figure 2*b*), the eveningside FACs (Figure 2*b*), and the cusp part FACs (Figure 2*a*). This is left for future studies.

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Fig. 1. Distributions of large-scale field-aligned currents (FACs) proposed in the dayside. (*a*) Five basic current systems observed for both northward and southward IMF cases: cusp part region 1 (cusp-1), noncusp part of dayside region 1 (R-1), dayside region 2 (R-2), cusp region or cusp part region 0 (cusp-0), and noncusp part of region 0 (R-0). There are several different names for these FACs (see text). (*b*) So-called DPY-FACs appear when the IMF B_y is strong. The figure shows only the cusp part.

Fig. 2. Proposed IMF B_y effect on the dayside large-scale field-aligned currents. (*a*) For the cusp part, the IMF B_y causes a shift of the demarcation line between prenoon side and postnoon side. (*b*) For the noncusp part, the IMF B_y causes tilts of the tail lobe, and that causes both latitudinal and longitudinal shifts of the locations of the region 1 and region 2 FACs. The region 0 FAC, which is much less significant than the region 1 and region 2 FACs in intensity, is not included in the figure. (*c*) If one combines the cusp part and the noncusp part, the region 1 FAC can be located poleward of the cusp part FACs. (*d*) The same as Figure 2*c* for IMF B_y negative case.

Fig. 3. Viking particle and magnetic field (north, east, downward components) data for the cusp crossing of orbit 871. The open arrows in the magnetic field data indicate the direction (upward and downward) of the field-aligned currents obtained from the gradient of B_E. The IMF is northward $B_z = +6$ nT and dawnward $B_y = -3$ nT. The polar arc (0547-0550 UT) is accompanied by the downward FAC which is identified as DPY-FAC (or NBZ current). There is no FAC after 0550 UT, where particle data show a quiet polar cap. Thus so-called polar cap FAC is identified on the polar arc, and this noncusp part FAC contributes to the DPY-FAC as well as the cusp part (cusp-0) FAC, as is suggested in Figure 2.

Fig. 4. Viking particle and magnetic field data for the cusp crossing of orbit 1038. The IMF is southward $B_z = -2$ nT and duskward $B_y = +3$ nT. Upward field-aligned current is found inside the polar arc (1347-1353 UT) as well as in the mantle cusp (1342-1347 UT). Again, the DPY-FAC consists of the cusp-0 FAC and poleward-extended region 1 FAC as shown in Figure 2.

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