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Osaka University
ASYMPTOTIC BEHAVIOR AND AREA GROWTH OF MINIMAL SURFACES IN $H^n$

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Let $H^n$ be the hyperbolic $n$-space of constant curvature $-1$. We identify $H^n$ with the unit ball in the Euclidean $n$-space $\mathbb{R}^n$ via the Poincare model, i.e., $H^n = (B^n(1), \frac{sd^2}{(1-r^2)^2})$, where $ds^2$ is the Euclidean metric and $r$ is the Euclidean distance from the origin. The sphere $\partial B^n(1)$ is called the sphere at infinity and denoted by $S^{n-1}(\infty)$. It represents the asymptotic classes of geodesics in $H^n$. Let $M$ be an immersed complete minimal surface in $H^n$. The intersection of the closure of $M$ in the Euclidean topology with $S^{n-1}(\infty)$ can be seen as the asymptotic boundary of $M$. In [1], M.T. Anderson established the general existence theorem of complete area-minimizing current with prescribed asymptotic boundary, which enclosed the following result as a special case:

Let $C$ be a smooth closed curve (or more generally, closed 1-current) in $S^{n-1}(\infty)$, then there is a complete area-minimizing smooth surface $M$ with asymptotic boundary $C$.

This paper is concerned with the asymptotic behaviour of complete minimal surfaces in $H^n$. This is partially suggested by the “good” behaviour at infinity of complete minimal surfaces in $\mathbb{R}^n$ with finite total Gaussian curvature, namely, the tangent cone at infinity of a such minimal surface is uniquely a collection of 2-plane with multiplicities (see [2],[3],[5]). But the situation is different in $H^n$. One of the differences is the above mentioned result of Anderson; another is that the total Gaussian curvature of complete minimal surface in $H^n$ is infinite (this can be seen by the Gauss equation). We will study a class of minimal surfaces in $H^n$ with minimal area growth (see §1 of the definition). We present some geometric descriptions of such surfaces, and find that the “length” of their asymptotic boundary in $S^{n-1}(\infty)$ are finite (see Theorem 3.2). A corollary of our theorems is (Corollary 3.3)

Let $M$ be a properly immersed complete and oriented minimal surface in $H^n$ with Gaussian curvature $K$. Suppose $M$ has finite topological type and

$$-\int_M (1 + K) < +\infty,$$
then the asymptotic boundary of $M$ is a rectifiable 1-varifold with finite mass.

This paper is organized as follows. In section 1, we introduce some basic properties of minimal surfaces in $H^n$. In section 2 we present Theorem 2.1 which establishes a relation between the area growth of a minimal surface in $H^n$ and some weighted $L^2$-norm of its second fundamental form. The corresponding result of minimal surfaces in $\mathbb{R}^n$ was obtained in a previous paper [2]. In section 3, we discuss the Euclidean area and boundary structure of a minimal surface in $H^n$. Since the asymptotic boundary of minimal surface in $H^n$ is not a smooth curve in general. Some concepts from geometric measure theory should be employed in the proof of the theorem. We refer to [8] for a reference of definitions and terminology of geometric measure theory.

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1. Preliminaries

Throughout this paper $H^n$ denotes the hyperbolic $n$-space of constant curvature $-1$, and $M$ an oriented and properly immersed complete minimal surface in $H^n$. We first recall some well-known facts.

**Proposition 1.1.** (Monotonicity formula, Theorem 1 of [1]) Let $B(t)$ be the geodesic ball of $H^n$ centered at a fixed point and radius $t$, and set $M(t) = M \cap B(t)$ and $v(t) = \text{Area}(M(t))$. Then the function

$$\frac{v(t)}{\cosh t - 1}$$

is monotone non-decreasing in $t$, particularly,

$$v'(t) \cosh t - v(t) \sinh t \geq v'(t).$$

**Definition 1.2.** $M$ is said to have minimal area growth if

$$\sup_{} \frac{v(t)}{\cosh t - 1} < +\infty.$$  

The following proposition is a direct consequence of the definitions of the Hessian and the second fundamental form, for the proof see [6].
Proposition 1.3. Let \( A \) be the second fundamental form of \( M \), \( \rho \) the distance function of \( \mathbb{H}^n \) from a fixed point and \( \nabla \) the covariant derivative of \( M \), then
\[
(\nabla^2 \rho)(e, e) = \coth \rho(1 - (e, \nabla \rho)^2) + \langle A(e, e), \nabla^\perp \rho \rangle,
\]
for any unit tangent vector \( e \) of \( M \), where \( \nabla^\perp \rho \) is the normal projection of \( \text{Grad}_n \rho \) to \( M \).

The restriction of distance \( \rho \) on \( M \) is smooth. By Sard’s theorem, for almost all \( t > 0 \), \( M(t) \) is a compact surface with boundary \( \partial M(t) \) being an immersed closed curve. Denote the geodesic curvature of \( \partial M(t) \) by \( k_g^t \). Then the Gauss-Bonnet formula is
\[
(1.1) \quad \int_{\partial M(t)} k_g^t + \int_{M(t)} K = 2\pi \chi(M(t)),
\]
where \( K \) is the Gaussian curvature of \( M \), and \( \chi(M(t)) \) is the Euler characteristic of \( M(t) \). Substituting the Gauss equation \( K = -1 - \frac{1}{2} |A|^2 \) into (1.1), and putting \( R(t) = \int_{M(t)} |A|^2 \), then
\[
(1.2) \quad v(t) + \frac{1}{2} R(t) + 2\pi \chi(M(t)) = \int_{\partial M(t)} k_g^t.
\]
Suppose \( e \) is tangent to \( \partial M(t) \). Then, \( \frac{\nabla \rho}{|\nabla \rho|} \) being normal to \( \partial M(t) \) in \( M \), the expression of \( k_g^t \) is
\[
(1.3) \quad k_g^t = -\langle \nabla e, \frac{\nabla \rho}{|\nabla \rho|} \rangle
= \frac{1}{|\nabla \rho|} (\nabla^2 \rho)(e, e)
= \frac{1}{|\nabla \rho|} (\coth \rho + \langle A(e, e), \nabla^\perp \rho \rangle),
\]
where the last equality is followed by Proposition 1.2.

By the co-area formula (see [8]), \( v'(t) = \int_{\partial M(t)} \frac{1}{|\nabla \rho|} \). Substituting (1.3) into (1.2), we obtain

Proposition 1.4. For almost all \( t > 0 \),
\[
v(t) + \frac{1}{2} R(t) + 2\pi \chi(M(t)) = v'(t) \coth t - \int_{\partial M(t)} \langle A(\frac{\nabla \rho}{|\nabla \rho|}, \frac{\nabla \rho}{|\nabla \rho|}, \nabla^\perp \rho \rangle).
\]
2. Area growth estimate

In this section we prove the following theorem, which is analogous to Theorem 1 of [2].

**Theorem 2.1.** Let $M$ be a properly immersed complete minimal surface in $\mathbb{H}^n$. Suppose $M$ is of finite topological type. Then $M$ has minimal area growth if and only if

$$\int_M e^{-\rho(x)} |A|^2(x) dx < +\infty,$$

where $A$ is the second fundamental form of $M$ and $\rho$ is the distance function of $\mathbb{H}^n$ to a fixed point.

**Lemma 2.2.** For $t > s > t_0 \geq 0$,

$$\int_{M(t)-M(t_0)} \frac{\cosh \rho}{\cosh^2 t} - \frac{\cosh \rho}{\cosh^2 s} = \int_{M(t)-M(s)} \frac{1 + |\nabla \rho|^2 \sinh^2 \rho}{\cosh^3 \rho} + \int_s^t \frac{\sinh t \sinh u}{\cosh^3 u} \int_{\partial M(t_0)} |\nabla \rho|.$$

Proof. By the minimality of $M$ and Proposition 1.3, we observe that

$$\Delta \rho = (2 - |\nabla \rho|^2) \coth \rho,$$

where $\Delta$ is the Laplacian of $M$. It yields

$$\Delta \cosh \rho = 2 \cosh \rho. \tag{2.1}$$

Integrating (2.1) over $M(t) - M(t_0)$ and by using Green’s formula, we have

$$2 \int_{M(t)-M(t_0)} \cosh \rho = \int_{\partial M(t)} |\nabla \rho| \sinh \rho - \int_{\partial M(t_0)} |\nabla \rho| \sinh \rho. \tag{2.2}$$

The co-area formula ([8]) leads

$$\frac{d}{dt} \left( \frac{\int_{M(t)-M(t_0)} \cosh \rho}{\cosh^2 t} \right)$$

$$= \frac{1}{\cosh^3 t} \left( \cosh t \int_{\partial M(t)} \frac{\cosh \rho}{|\nabla \rho|} - 2 \sinh t \int_{M(t)-M(t_0)} \cosh \rho \right)$$

$$= \frac{1}{\cosh^3 t} \left( \int_{\partial M(t)} \left( \frac{\cosh^2 t}{|\nabla \rho|} - |\nabla \rho| \sinh^2 t \right) + \sinh t_0 \sinh t \int_{\partial M(t_0)} |\nabla \rho| \right)$$

$$= \frac{1}{\cosh^3 t} \left( \int_{\partial M(t)} \frac{1}{|\nabla \rho|} \left( 1 + |\nabla \rho|^2 \sinh^2 t \right) + \sinh t_0 \sinh t \int_{\partial M(t_0)} |\nabla \rho| \right). \tag{2.3}$$
The lemma is then proved by integrating (2.3) from $s$ to $t$ and the co-area formula.

Proof of Theorem 2.1. By the co-area formula,

$$
\int_{M(t)} e^{-\rho}|A|^2 = \int_0^t e^{-s} R'(s) ds
$$

(2.4)

$$
= e^{-t} R(t) + \int_0^t e^{-s} R(s) ds.
$$

We rewrite Proposition 1.4 as

$$
\frac{v'(t) \cosh t - v(t) \sinh t}{\sinh t} = \frac{1}{2} R(t) + 2\pi \chi(M(t))
$$

(2.5)

$$
+ \int_{\partial M(t)} \langle A(\nabla\rho \mid \nabla\rho \mid \nabla^\perp\rho \rangle.
$$

From now on, $C_i (i = 1, 2, \ldots)$ will be denoted as constants independent of $t$.

If $\int_M e^{-\rho(x)}|A|^2(x) dx < +\infty$, by (2.5) we have

$$
\frac{d}{dt} \frac{v(t)}{\cosh t} \leq \frac{\sinh t}{\cosh^2 t} \left( \frac{1}{2} R(t) + 2\pi \chi(M(t)) \right) + \int_{\partial M(t)} |A| \frac{|\nabla^\perp\rho| \sinh t}{\cosh^2 t}.
$$

(2.6)

Integrating (2.6) from 0 to $t$ and by the co-area formula,

$$
\frac{v(t)}{\cosh t} \leq 2 \int_0^t \frac{1}{2} R(s) + 2\pi \chi(M(s)) e^{-s} ds + \int_{M(t)} |A| \frac{|\nabla^\perp\rho| \sinh \rho}{\cosh^2 \rho}
$$

(2.7)

Since $\chi(M(t)) \leq 1$, by using the Schwarz inequality, (2.7) and the hypothesis, we have

$$
\frac{v(t)}{\cosh t} \leq C_1 + \left( \int_{M(t)} \frac{|A|^2}{\cosh \rho} \right)^{\frac{1}{2}} \left( \int_{M(t)} \frac{|\nabla^\perp\rho|^2 \sinh^2 \rho}{\cosh^3 \rho} \right)^{\frac{1}{2}}
$$

(2.8)

$$
\leq C_1 + C_2 \left( \int_{M(t)} \frac{\cosh \rho}{\cosh^2 t} \right)^{\frac{1}{2}} \quad \text{(by Lemma 2.2)}
$$

$$
\leq C_1 + C_2 \left( \frac{v(t)}{\cosh t} \right)^{\frac{1}{2}}.
$$

Thus by the monotonicity of $\frac{v(t)}{\cosh t}$ we see either $\sup \frac{v(t)}{\cosh t} \leq C_1^2$ or, when $t$ is large enough, $C_1^2 < \frac{v(t)}{\cosh t}$, so

$$
\frac{v(t)}{\cosh t} \leq \left( \frac{v(t)}{\cosh t} \right)^{\frac{1}{2}} + C_2 \left( \frac{v(t)}{\cosh t} \right)^{\frac{1}{2}}.
$$
It follows
\[ \sup \frac{v(t)}{\cosh t} \leq \max \{ C_1^2, (1 + C_2)^2 \}, \]
this proves that \( M \) has minimal area growth.

Conversely, when \( \sup \frac{v(t)}{\cosh t} < \infty \), it suffices to show \( \int_0^\infty e^{-t} R(t) dt < +\infty \).
Indeed, this implies that there is a sequence \( \{ t_i \} \) tending to infinity such that
\( e^{-t_i} R(t_i) \to 0 \) as \( i \to \infty \),
taking \( t = t_i \) in \( (2.4) \) then letting \( i \) tending to infinity, the theorem follows.

We derive from \((2.5)\) that
\[ \frac{1}{2} R(t)e^{-t} \leq -2\pi \chi(M) e^{-t} + \frac{e^{-t} \cosh^2 t}{\sinh t} \left( \frac{v(t)}{\cosh t} \right) + \int_{\partial M(t)} \frac{e^{-t} |A| |\nabla^2 \rho|}{|\nabla \rho|}, \]
and we integrate above inequality from 0 to \( t \). Then, since the integrals of the first two terms in the right hand side of \((2.9)\) is bounded above, we have
\[ \frac{1}{2} \int_0^t e^{-s} R(s) ds \leq C_3 + \int_{M(t)} e^{-s} |A| |\nabla^2 \rho| \]
\[ \leq C_3 + \sqrt{\int_{M(t)} e^{-s} |A|^2} \int_{M(t)} e^{-s} |\nabla^2 \rho|^2 \]
\[ \leq C_3 + C_4 \sqrt{\int_{M(t)} e^{-s} |A|^2}, \]
where the last inequality is followed by Lemma 2.2. For the convenience we set
\[ f(t) = \int_0^t e^{-s} R(s) ds. \]
Combining \((2.10)\) with \((2.4)\) we obtain
\[ \frac{1}{2} f(t) \leq C_3 + C_4 \sqrt{f(t) + f'(t)}. \]
We claim that either of the following holds:
(a): \( \int_0^\infty e^{-t} R(t) dt = \sup f(t) \leq 2C_3 \),
(b): there is a sequence \( \{ t_i \} \) tending to infinity such that \( f'(t_i) < f(t_i) \),
otherwise, there is a \( t_0 \) sufficient large such that \( f(t) < f'(t) \) and \( f(t) > 2C_3 \) when \( t \geq t_0 \), then by \((2.11)\)
\[ \frac{8C_4^2 f'(t)}{(f(t) - 2C_3)^2} \geq 1, \]
integrating this from \( t_0 \) to \( t \), we get
\[ 8C_4^2 \left( \frac{1}{f(t_0) - 2C_3} - \frac{1}{f(t) - 2C_3} \right) \geq t - t_0, \]
which contradicts with the fact that \( t \) is unbounded.

It remains to prove the theorem when (b) holds. Taking \( t = t_i \) in (2.11), one has

\[
(2.12) \quad \frac{1}{2} f(t_i) \leq C_3 + C_4 \sqrt{2f(t_i)}.
\]

If \( f(t_i) \to \infty \) as \( i \to \infty \), then dividing (2.12) by \( f(t_i) \) and letting \( i \to \infty \) would lead to an obvious contradiction. Hence \( \sup f(t) = \sup f(t_i) < \infty \) and the theorem follows.

### 3. Boundary behaviour of minimal surfaces

We regard \( \mathbb{H}^n \) as the Poincaré model, that is \( \mathbb{H}^n = (B^n(1), ds_H^2) \), where \( B^n(1) \) is the unit ball of \( \mathbb{R}^n \) and \( ds_H^2 = \frac{4}{(1 - r^2)^2} ds_E^2 \) with \( r \) being the Euclidean distance function from the origin. Here and after, the subscripts \( H \) and \( E \) indicate, respectively, the notations with respect to the hyperbolic metric and the Euclidean metric.

**Theorem 3.1.** Suppose \( M \to (B^n(1), ds_H) \) is a properly immersed complete minimal surface, then \( \sup \frac{\mathcal{H}(t)}{\cosh t} < \infty \). Then \( \text{Area}_E(M) < \infty \).

Proof. For \( p \in M \), the orthonormal basis \( e_1, e_2, (\text{or} \, \tilde{e}_1, \tilde{e}_2) \) of \( T_p M \) with respect to the Euclidean metric (or the hyperbolic metric) is related by

\[
\tilde{e}_i = \frac{1 - r^2(p)}{2} e_i, \quad i = 1, 2.
\]

Since \( r = \tanh \frac{\rho}{2} \), we have

\[
\nabla_E r(p) = \sum_{i=1}^{2} e_i(r) e_i = \sum_{i=1}^{2} \frac{4}{(1 - r^2)^2} \tilde{e}_i(r) \tilde{e}_i
\]

\[
= (1 + \cosh \rho)^2 \sum_{i=1}^{2} \tilde{e}_i(\tanh \frac{\rho}{2}) \tilde{e}_i
\]

\[
= (1 + \cosh \rho) \nabla_H \rho(p).
\]
It follows $|\nabla r|_E = |\nabla \rho|_H$. Then the co-area formula yields

$$v'_E(t) = \int_{\partial (M \cap B_E(t))} \frac{1}{|\nabla \rho|_H} \, ds_H$$

$$= \int_{\partial (M \cap B_E(\tanh \frac{t}{2}))} \frac{1}{|\nabla r|_E} \left(1 - \tanh^2 \frac{t}{2}\right) \, ds_E$$

$$= (\cosh t + 1)v'_E(\tanh \frac{t}{2}),$$

hence, by Proposition 1.1 we have

$$+\infty > \int_0^\infty \frac{v'_E(t)}{\cosh t} \, dt$$

$$\geq \int_0^\infty \frac{v'_E(t)}{\cosh^2 t} \, dt$$

$$= \int_0^\infty \frac{(1 + \cosh t)^2}{\cosh^2 t} v'_E(\tanh \frac{t}{2}) d(\tanh \frac{t}{2})$$

$$\geq \int_0^\infty v'_E(\tanh \frac{t}{2}) d(\tanh \frac{t}{2})$$

$$= \text{Area}_E(M).$$

This completes the proof.

Next we discuss the boundary behaviour of minimal surfaces. Following Anderson [1], the asymptotic boundary $\partial M$ of a complete minimal surface $M$ in $H^n$ is defined by

$$\partial M = \text{closure}(M) \cap S^{n-1}(\infty),$$

where the closure is taken in the Euclidean topology. When $M$ is properly immersed, then $\partial M$ is just the boundary of $M$ in the Euclidean space $R^n$.

**Theorem 3.2.** Let $M$ be an immersed complete minimal surface in $H^n$ with minimal area growth and finite topological type. Then the asymptotic boundary $\partial M$ of $M$ is a rectifiable 1-varifold with finite mass when $\partial M$ is considered as a subset of $S^{n-1}(\infty) \subset R^n$.

Proof. We claim that $M$ is properly immersed, which can be proved in the same way as the proof of Lemma 3 in [2]. Hence the boundary $\partial M(t)$ of $M(t) = M \cap B_{eH}(t)$ is a smooth closed curve, for almost all $t > 0$. Since

$$\text{length}_E(\partial M(t)) = \int_{\partial M(t)} ds_E = \frac{1}{1 + \cosh t} \text{length}_H(\partial M(t)).$$

By the minimal growth of the area, there is a sequence $\{t_i\}$ tending to infinity such that

$$\sup \text{length}_E(\partial M(t_i)) = \sup \frac{\text{length}_H(\partial M(t_i))}{\cosh t_i + 1} < \infty.$$
By the compactness theorem of current (Theorem 27.3 of [8]), there is a subsequence of \( \{ \partial M(t_i) \} \), denoted again by \( \{ \partial M(t_i) \} \), converges to an integer multiplicity 1-current as currents in \( \mathbb{R}^n \). If we regard \( \partial M(t_i) \) as a rectifiable 1-varifold in \( B^n(1) \subset \mathbb{R}^n \), then \( \{ \partial M(t_i) \} \) also converges to a rectifiable 1-varifold \( \mathcal{V} \) with integer multiplicity.

Suppose \( \mathcal{V} = \psi(\Sigma, \theta) \), where \( \Sigma = \text{support}(\mathcal{V}) \) and \( \theta \) is the multiplicity function of \( \mathcal{V} \). It is obvious that \( \Sigma \subset \partial M \). In the following we show actually \( \mathcal{V} = \psi(\partial M, \theta) \), then the theorem follows.

Denote \( \mathcal{H}^1 \) the 1-dimensional Hausdorff measure of \( \mathbb{R}^n \), and \( \mu_v \) the weight measure of \( \mathcal{V} \). By the convergence,

\[
\mathcal{H}^1|_{\partial M(t_i)} \to \mu_v \quad (i \to \infty)
\]
as the Radon measures. Suppose \( p \in \partial M - \Sigma \neq \phi \), there is a neighbourhood \( O \) of \( p \) in \( \mathbb{R}^n \) such that \( \Sigma \cap O = \phi \). We can choose \( O \) to be a ball in \( \mathbb{R}^n \) such that \( \partial O \cap B^n(1) \) is a hyperplane of \( \mathbb{H}^n \). Then

(3.4) \[
\text{length}_E(O \cap \partial M(t_i)) = \mathcal{H}^1(O \cap \partial M(t_i)) \to \mu_v(B_E(p, \varepsilon)) = 0.
\]

Since \( M \) has finite topological type, \( p \) represents an end \( V \) of \( M \), which is topologically an annulus. Let \( C_i = V \cap O \cap \partial M(t_i) \). If \( C_i \) is not a closed curve, taking \( p_i \in C_i \) such that \( p_i \to p \), then

\[
\text{length}_E(C_i) \geq \text{dist}_E(p_i, \partial O) \geq \text{dist}_E(p, \partial O) - \text{dist}_E(p_i, p).
\]

This implies by (3.4) that \( C_i \) is a closed curve when \( i \) is sufficiently large. By the convex hull property of minimal surface in \( \mathbb{H}^n \) (Lemma 5 of [1]), when \( i \geq i_0 \),

\[
V(t_i) \coloneqq V \cap (M(t_i) - M(t_{i_0})) \subset O.
\]

Applying Lemma 2.2 to \( V(t_i) \),

\[
\int_{V(t_i)} \cosh \rho ds^2_H \geq \cosh^2 \rho \int_{V(t_i)} \frac{1 + |\nabla \rho|^2 \sinh^2 \rho}{\cosh^2 \rho} ds^2_H.
\]

Now (2.2) implies

\[
\mathcal{H}^1(C_i) = \frac{\text{length}_H(C_i)}{1 + \cosh t_i} \geq \frac{1}{\sinh t_i (1 + \cosh t_i)} \int_{V(t_i)} \cosh \rho ds^2_H \geq \frac{\cosh^2 t_i}{\sinh t_i (1 + \cosh t_i)} \int_{V(t_i)} 1 + |\nabla \rho|^2 \sinh^2 \rho \cosh^2 \rho ds^2_H,
\]

which contradicts (3.4). This completes the proof of the theorem.
Corollary 3.3. Let $M$ be a properly immersed complete and oriented minimal surface in $H^n$ with Gaussian curvature $K$. Suppose $M$ has finite topological type and

$$-\int_M (1 + K) < +\infty,$$

then the asymptotic boundary of $M$ is a rectifiable 1-varifold with finite mass.

Proof. By the hypothesis and the Gauss equation,

$$\int_M |A|^2 < \infty.$$ 

Therefore the corollary is followed by Theorem 2.2 and Theorem 3.2.

Remark 3.4. 1. Let $M$ be a properly immersed complete minimal surface in $H^n$ with minimal area growth and finite topological type. By Theorem 3.1, $M$ is a 2-current with finite mass when $M$ is considered as a current in $\mathbb{R}^n$. Then Theorem 3.2 implies readily that asymptotic boundary $\partial M$ coincides with the boundary current of $M$ in $\mathbb{R}^n$, which generalizes Proposition 6 of [1].

2: It would be an interesting question whether the following equality holds for the properly immersed complete minimal surfaces in $H^n$ with minimal area growth:

$$\sup \frac{v(t)}{\cosh t - 1} = \int_{\partial M} \theta \, dH^1 \text{ (mass of } V).$$

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References

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