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# SMOOTH 2-KNOTS IN $S^2 \times S^2$ WITH SIMPLY CONNECTED COMPLEMENTS ARE TOPOLOGICALLY UNIQUE

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ABSTRACT. For a given primitive homology class $\xi$ of $H_2(S^2 \times S^2; \mathbf{Z})$, we show that there exists only one smoothly embedded 2-sphere in $S^2 \times S^2$, up to homeomorphism, which represents $\xi$ and whose complement is simply connected.

## 1. INTRODUCTION

It is a consequence of Freedman's theorem [3] that $(\mathbf{C}P^2, S)$, where $S$ is a smoothly embedded 2-sphere in $\mathbf{C}P^2$ representing a generator of $H_2(\mathbf{C}P^2; \mathbf{Z})$, is pairwise homeomorphic to $(\mathbf{C}P^2, \mathbf{C}P^1)$. (See [6].) In this note, we will study the extent to which this kind of unknotting theorem holds in $S^2 \times S^2$.

Kuga [7] has characterized those homology classes in $S^2 \times S^2$ that can be represented by smoothly embedded 2-spheres. Let $\zeta$ and $\eta$ be natural generators of $H_2(S^2 \times S^2; \mathbf{Z})$ representing the cross-section and fiber of the projection $S^2 \times S^2 \to S^2$ onto the first factor with $\zeta \cdot \zeta = \eta \cdot \eta = 0$ and $\zeta \cdot \eta = \eta \cdot \zeta = 1$. He has shown that $\xi = p\zeta + q\eta$, $p, q \in \mathbf{Z}$, can be represented by a smoothly embedded 2-sphere in $S^2 \times S^2$ if and only if $|p| \leq 1$ or $|q| \leq 1$. If we let $S$ be a smoothly embedded 2-sphere in $S^2 \times S^2$ representing $\xi \in H_2(S^2 \times S^2; \mathbf{Z})$, we will call $S = (S^2 \times S^2, S)$ a 2-knot in $S^2 \times S^2$ representing $\xi$. It is easy to see that if the class $\xi$ is not primitive, then $H_1(S^2 \times S^2 - S; \mathbf{Z})$ is nonzero. We are interested in 2-knots with simply connected complement, so we may assume, without loss of generality, that $S$ represents the class $\xi = \zeta + p\eta$ for some $p \geq 0$. There is a standard 2-knot $\Sigma_p$ in $S^2 \times S^2$ representing $\xi = \zeta + p\eta$, which is the image of $\phi_p: S^2 \to S^2 \times S^2$, defined by $\phi_p(x) = (x, \rho_p(x))$. Here $\rho_p: S^2 \to S^2$ is the canonical smooth map of degree $p$. We note that the exterior of $\Sigma_p$ in $S^2 \times S^2$ is diffeomorphic to a $D^2$-bundle $D(2p)$ over $S^2$ with

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the Euler number $2p$. Our main result is the following:

**Theorem.** *Let $S$ be a 2-knot in $S^2 \times S^2$. Then $\pi_1(S^2 \times S^2 - S)$ is trivial if and only if there exists a homeomorphism of pairs*

$$\varphi\colon (S^2 \times S^2, S) \to (S^2 \times S^2, \Sigma_p)$$

*for some nonnegative integer $p$.*

Let $K$ be a 2-knot in $S^4$ and $S$ a 2-knot in $S^2 \times S^2$. Then we obtain another 2-knot $S'$ in $S^2 \times S^2$ by forming the connected sum of pairs, $(S^2 \times S^2, S)$ and $(S^4, K)$; i.e., $(S^2 \times S^2, S') = (S^2 \times S^2, S)\#(S^4, K)$. We shall say that $S' = (S^2 \times S^2, S')$ is obtained by the action of local 2-knot $K$ on a 2-knot $S$ in $S^2 \times S^2$. Thus the semigroup of local 2-knots acts on 2-knots in $S^2 \times S^2$. However, this action does not always give a new 2-knot in $S^2 \times S^2$. In fact

**Corollary 1.** *The action of local 2-knots on a 2-knot in $S^2 \times S^2$ with simply connected complement is trivial.*

In §3 we present proofs of the Theorem and Corollary 1, and in §4 we construct 2-knots in $S^2 \times S^2$ representing $\zeta$ whose complements are not simply connected. We note that the above results hold in the case of locally flat embeddings.

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## 2. Preliminaries

The principal SO(2)-bundles over $S^2$ are classified by the Euler number $\in \mathbf{Z} \cong \pi_1(\mathrm{SO}(2))$. Let $D(m)$ be the total space of the associated $D^2$-bundle over $S^2$ indexed by $m \in \mathbf{Z}$. If we let $\nu\colon S^2 \to D(m)$ be the zero-section, it represents a generator of $H_2(D(m); \mathbf{Z})$ and its selfintersection number is $m$. We note that the boundary of $D(m)$ is the lens space $L(m, m-1)$. Here $L(0, -1)$ is $S^2 \times S^1$ and $L(1, 0)$ is $S^3$.

Let $S$ be a 2-knot in $S^2 \times S^2$ whose selfintersection number is $m$. Then a tubular neighborhood of $S$ in $S^2 \times S^2$ is diffeomorphic to $D(m)$. Let $E$ be the exterior of $S$ in $S^2 \times S^2$. By identifying the boundary $L(m, m-1)$ of $D(m)$ with the boundary $L(m, m-1)$ of $E$ via some diffeomorphism $h\colon L(m, m-1) \to L(m, m-1)$, every 2-knot in $S^2 \times S^2$ with exterior $E$ is obtained. By the isotopy extension theorem, it is easily seen that the homeomorphism type of 2-knot in $S^2 \times S^2$ obtained in this manner depends only on the isotopy class of the diffeomorphism used to identify the two boundaries. Thus we will need the following propositions.

Let $\mathscr{D}(L(m, m-1))$ be the group of diffeomorphisms of $L(m, m-1)$ onto itself, and let $\mathscr{D}_0(L(m, m-1))$ be the normal subgroup of $\mathscr{D}(L(m, m-1))$ consisting of those diffeomorphisms which are isotopic to the identity. Then the quotient group

$$\mathcal{M}(L(m, m-1)) = \mathcal{D}(L(m, m-1))/\mathcal{D}_0(L(m, m-1))$$

is the diffeotopy group of $L(m, m-1)$.

Let $r: S^2 \to S^2$ be the antipodal map, and $s: S^1 \to S^1$ the map induced on the unit circle in the complex plane by complex conjugation. Let $\mathcal{M}'$ be the subgroup of $\mathcal{M}(S^2 \times S^1)$ generated by the isotopy classes of the maps $(r, \mathrm{id})$ and $(\mathrm{id}, s)$. Then $\mathcal{M}' \cong \mathbf{Z}_2 \oplus \mathbf{Z}_2$.

**Proposition 2.1** ([4]).

$$\mathcal{M}(S^2 \times S^1) \cong \mathbf{Z}_2 \oplus \mathbf{Z}_2 \oplus \mathbf{Z}_2 .$$

The first two factors correspond to $\mathcal{M}'$ and the third is generated by $\tau$, defined by

$$\tau(x, \theta) = (\rho(\theta)(x), \theta),$$

where $\rho(\theta)$ is rotation of $S^2$ about its poles through the angle $\theta$. We note that the maps $(r, \mathrm{id})$ and $(\mathrm{id}, s)$ extend to diffeomorphisms of $(S^2 \times D^2, S^2 \times \{0\})$ but $\tau$ does not extend to a continuous map of $S^2 \times D^2$ onto itself.

**Proposition 2.2** ([1, 5]). *Let* $|m| \geq 2$. *Then*

$$\mathcal{M}(L(m, m-1)) \cong \mathbf{Z}_2 .$$

When we view $L(m, m-1)$ as the associated $S^1$-bundle over $S^2$, $\mathcal{M}(L(m, m-1))$ is generated by the diffeomorphisms of $L(m, m-1)$ onto itself whose restriction to each fiber corresponds to the map induced on $S^1$ by complex conjugation. Hence an element of $\mathcal{M}(L(m, m-1))$ extends to a diffeomorphism of $(D(m), \nu(S^2))$.

## 3. Proof of the main theorem

**Lemma.** *Let $S$ be a 2-knot in $S^2 \times S^2$ with simply connected complement. Then, the exterior $E$ of $S$ in $S^2 \times S^2$ is homeomorphic to $D(2p)$ for some nonnegative integer $p$.*

*Proof*. Without loss of generality we may assume that $S$ represents $\xi = \zeta + p\eta$ for some nonnegative integer $p$. Let $N(S)$ be a tubular neighborhood of $S$ in $S^2 \times S^2$. Then $N(S)$ is diffeomorphic to $D(2p)$, so the boundary $\partial E$ of $E$ is the lens space $L(2p, 2p-1)$. By the Poincaré duality and excision,

$$H^2(E) \cong H_2(E, \partial E) \cong H_2(S^2 \times S^2, N)$$

and

$$H_3(S^2 \times S^2, N) \cong H_3(E, \partial E) \cong H^1(E) \cong 0 .$$

Thus the homology exact sequence of the pair $(S^2 \times S^2, N)$ gives us a short exact sequence

$$0 \to H_2(N) \to H_2(S^2 \times S^2) \to H_2(S^2 \times S^2, N) \to 0 .$$

Since $\xi$ is a generator of $H_2(S^2 \times S^2; \mathbf{Z})$, $H_2(S^2 \times S^2, N) \cong \mathbf{Z}$. Hence $H_2(E; \mathbf{Z}) \cong H_2(E, \partial E; \mathbf{Z}) \cong \mathbf{Z}$. First we show the case of $p = 0$. Consider the following exact sequence of the pair $(E, \partial E)$,

$$\begin{array}{ccccccccccc} 0 & \rightarrow & H_2(\partial E) & \rightarrow & H_2(E) & \xrightarrow{j} & H_2(E, \partial E) & \rightarrow & H_1(\partial E) & \rightarrow & 0. \\ & & \cong & & \cong & & \cong & & \cong & & \\ & & \mathbf{Z} & & \mathbf{Z} & & \mathbf{Z} & & \mathbf{Z} & & \end{array}$$

Hence $j$ is the zero-map, and the intersection form $(H_2(E; \mathbf{Z}), \cdot)$ is isomorphic to $(\mathbf{Z}, (0))$, where $(0): \mathbf{Z} \times \mathbf{Z} \rightarrow \mathbf{Z}$ is the zero map. Therefore it follows from Remarks (5.3) of [2] that $E$ is homeomorphic to $D(0) = S^2 \times D^2$. Next we show the case of $p \neq 0$. Then $\xi$ and $\eta$ generate $H_2(S^2 \times S^2; \mathbf{Z})$, and the intersection form $(H_2(E; \mathbf{Z}), \cdot)$ is isomorphic to $(\mathbf{Z}, (2p))$, where $(2p): \mathbf{Z} \times \mathbf{Z} \rightarrow \mathbf{Z}$ is the bilinear form defined by $(2p)(1, 1) = 2p$. Moreover $H_2(E, \partial E; \mathbf{Z}) \cong \mathbf{Z}$ is generated by the class $w$ represented by $(\{*\} \times S^2) \cap E$. Since $\xi \cdot \eta = 1$, $\partial w \in H_1(L(2p, 2p-1); \mathbf{Z})$ is represented by the $\partial D^2$-fiber of the $D^2$-bundle $N(S)$ over the 2-sphere $S$. Hence, Example (5.4) and Remarks (5.6) of [2] imply that $E$ is homeomorphic to $D(2p)$. This completes the proof. □

*Proof of Theorem.* The "if" part of the theorem is trivial. Next we suppose that $\pi_1(S^2 \times S^2 - S)$ is trivial. Since a tubular neighborhood of $S$ in $S^2 \times S^2$ is diffeomorphic to $D(2p)$,

$$(S^2 \times S^2, S) \cong (D(2p) \cup_\gamma E, \nu(S^2)),$$

where $\gamma: L(2p, 2p-1) \rightarrow L(2p, 2p-1)$ is some "gluing" diffeomorphism and $\nu: S^2 \rightarrow D(2p)$ is the zero-section. By the Lemma, there exists a homeomorphism $h: E \rightarrow D(2p)$. Let $\tilde{h}$ be the restriction of $h$ to $\partial E$. It is easily seen that $D(2p) \cup_\gamma E$ is homeomorphic to $D(2p) \cup_{\tilde{h} \circ \gamma} D(2p)$.

First we show the case of $p = 0$. Since the maps $(r, \mathrm{id})$ and $(\mathrm{id}, s)$ extend to diffeomorphisms of $(S^2 \times D^2, S^2 \times \{0\})$, it is sufficient to consider the case of $[\tilde{h} \circ \gamma] \in \mathscr{M}'$ or $[\tilde{h} \circ \gamma] = [\tau] \in \mathscr{M}(S^2 \times S^1)$. We suppose $[\tilde{h} \circ \gamma] = [\tau]$, and set $M = S^2 \times D^2 \cup_{\tilde{h} \circ \gamma} S^2 \times D^2$. Then $M$ is an $S^2$-bundle over $S^2$. Since $[\tau]$ corresponds to the nontrivial element of $\pi_1(\mathrm{SO}(3)) \cong \mathbf{Z}_2$, the second Stiefel-Whitney class $w_2(M)$ of $M$ is nontrivial. This contradicts the fact that $M$ is homeomorphic to $S^2 \times S^2$. Thus we may assume $[\tilde{h} \circ \gamma] \in \mathscr{M}'$, and $\tilde{h} \circ \gamma$ extends to a diffeomorphism $g$ of $(S^2 \times D^2, S^2 \times \{0\})$. We define a required homeomorphism

$$\varphi: (S^2 \times D^2 \cup_\gamma E, S^2 \times \{0\}) \rightarrow (S^2 \times D^2 \cup_{\mathrm{id}} S^2 \times D^2, S^2 \times \{0\})$$

by setting

$$\varphi = \begin{cases} g & \text{on } S^2 \times D^2, \\ h & \text{on } E. \end{cases}$$

Hence $(S^2 \times S^2, S)$ is pairwise homeomorphic to $(S^2 \times S^2, \Sigma_0)$.

Using the remarks after Proposition 2.2, we can show the case of $p \neq 0$ in the same manner as above. This completes the proof of the theorem. □

*Proof of Corollary* 1. Let $S$ be a 2-knot in $S^2 \times S^2$ with exterior $E(S)$, and let $K$ be a 2-knot in $S^4$ with exterior $E(K)$. Set $(S^2 \times S^2, S') = (S^2 \times S^2, S)\#(S^4, K)$ and let $E(S')$ be the exterior of $S'$ in $S^2 \times S^2$. Then $E(S') = E(S) \cup_T E(K)$, where $T = \partial E(S) \cap \partial E(K)$ is a meridional solid torus. Since $\pi_1(E(S))$ is trivial and $\pi_1(E(K))$ is normally generated by the class of the meridian, it follows from van Kampen's theorem that $\pi_1(E(S))$ is trivial. Thus the result follows from our theorem. □

Let $\rho_p: S^2 \to S^2$ be the canonical smooth map of degree $p$; we define $\phi_{p,q}: S^2 \to S^2 \times S^2$ by $\phi_{p,q}(x) = (\rho_p(x), \rho_q(x))$. If $|p| = 1$ or $|q| = 1$, then the image $\Sigma_{p,q}$ of $\phi_{p,q}$ is a 2-knot in $S^2 \times S^2$ representing $p\zeta + q\eta$, whose complement is simiply connected. We note that $\Sigma_p = \Sigma_{1,p} = \Sigma_{-1,-p} \subset S^2 \times S^2$ and $\Sigma_{p,1} = \Sigma_{-p,-1} \subset S^2 \times S^2$ as sets.

**Corollary 2.** *Let $S$ be a 2-knot in $S^2 \times S^2$. If $\pi_1(S^2 \times S^2 - S)$ is trivial, then $S$ is topologically ambient isotopic to $\Sigma_{1,p}$ or $\Sigma_{p,1}$ for some integer $p$.*

*Proof.* It follows from Theorem 1.1 of [10] that the homeotopy group of $S^2 \times S^2$ is isomorphic to

$$\operatorname{Aut}\left(H_2, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\right) = \left\{A \in \mathrm{GL}(2, \mathbf{Z}); {}^tA\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\right\}$$
$$= \left\{\pm\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \pm\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\right\}.$$

Since $\pi_1(S^2 \times S^2 - S)$ is trivial, we let $S$ represent $\zeta + p\eta$ for some integer $p$. In fact we can show other cases without any essential change. It is easy to see from the Theorem that there is a homeomorphism of pairs, $\varphi: (S^2 \times S^2, S) \to (S^2 \times S^2, \Sigma_{1,p})$, such that $\varphi_*[S] = [\Sigma_{1,p}] = \zeta + p\eta$. Hence, in $\operatorname{Aut}(H_2, (\begin{smallmatrix} 0 & 1 \\ 1 & 0 \end{smallmatrix}))$

$$\varphi_* = \begin{cases} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \text{ or } \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} & \text{if } p = 1, \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \text{if } p \neq 1. \end{cases}$$

Therefore if $p \neq 1$, then $\varphi$ is isotopic to the identity. If $p = 1$, then there is a homeomorphism of pairs, $\psi: (S^2 \times S^2, \Sigma_{1,p}) \to (S^2 \times S^2, \Sigma_{1,p})$, such that $\psi_* = (\begin{smallmatrix} 0 & 1 \\ 1 & 0 \end{smallmatrix})$. Hence, by composing $\varphi$ (if necessary) with $\psi$, $\varphi_* = (\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix})$, and so $\varphi$ is isotopic to the identity. □

## 4. Examples of 2-knots in $S^2 \times S^2$

We give examples of 2-knots in $S^2 \times S^2$ whose complements are not simply connected. We construct a 2-knot in $S^2 \times S^2$ in the same manner as in [8].

Let $K$ be a 2-knot in $S^4$ and $C$ a smoothly embedded circle in $S^4$ disjoint from $K$. Then we may assume that $C$ is standardly embedded in $S^4$. The exterior of $C$ in $S^4$ is diffeomorphic to $S^2 \times D^2$. Let $\zeta$ denote the generator of $H_2(S^4 - C)$. Since $K$ is contained in $S^2 \times D^2$, this gives us a 2-knot $S$ in $S^2 \times S^2 = S^2 \times D^2 \cup S^2 \times D^2$. It follows from van Kampen's theorem that $\pi_1(S^2 \times S^2 - S)$ is isomorphic to $\pi_1(S^4 - K)/H$, where $H$ is the normal closure generated by the element represented by $C$ in $\pi_1(S^4 - K)$.

**Proposition 4.1.** *If $C$ is homologous in $S^4 - K$ to a meridian of $K$, then the 2-knot $S$ in $S^2 \times S^2$ constructed from $K$ and $C$ represents $\zeta$.*

*Proof.* We consider the following exact sequences,

$$\begin{array}{lllll} \to & H_2(K) \xrightarrow{i} H_2(S^4 - C) & \to & H_2(S^4 - C, K) & \to 0, \\ \to & H^1(S^4 - K) \xrightarrow{j} H^1(C) & \to & H^2(S^4 - K, C) & \to 0. \end{array}$$

The 2-knot $S$ in $S^2 \times S^2$ represents $\zeta$ if and only if $i$ is an isomorphism. By the duality, $H_2(S^4 - C, K) \cong H^2(S^4 - K, C)$. Since

$$H_2(K) \cong H_2(S^4 - C) \cong H^1(S^4 - K) \cong H^1(C) \cong \mathbf{Z},$$

$\mathbf{Z}/i(\mathbf{Z}) \cong \mathbf{Z}/j(\mathbf{Z})$. Hence $i$ is an isomorphism if and only if $j$ is also. Meanwhile if $C$ is homologous in $S^4 - K$ to a meridian of $K$, $j$ is an isomorphism. This completes the proof. □

*Remark.* In general, if $C$ is homologous in $S^4 - K$ to the $p$th power of a meridian of $K$, then $S$ represents $p\zeta$.

**Example 4.1.** Let $K$ be the 5-twist-spun 2-knot of the trefoil [11]. Then $\pi_1(S^4 - K) \cong \mathbf{Z} \times \mathscr{D}$, where $\mathscr{D}$ is the binary dodecahedral group $\langle a, b; a^3 = b^5 = (ab)^2 \rangle$, and $\mathbf{Z}$ is generated by $\mu$, which is homologous to a meridian of $K$. Then the subgroup generated by $c = a^3$ in $\mathscr{D}$ is the center of $\mathscr{D}$. Let $C$ be an embedded circle representing $\mu c^{-1}$ in $\pi_1(S^4 - K)$ and $H$ the normal closure generated by $\mu c^{-1}$ in $\pi_1(S^4 - K)$. The 2-knot $S$ in $S^2 \times S^2$ constructed from $K \subset S^4$ and $C \subset S^4$ represents $\zeta$, and $\pi_1(S^2 \times S^2 - S) \cong \pi_1(S^4 - K)/H \cong \mathscr{D}$. Therefore, $(S^2 \times S^2, S)$ is not pairwise homeomorphic to $(S^2 \times S^2, \Sigma_0)$.

**Example 4.2.** Let $K$ be a classical knot and let $m$ and $l$ be the meridian-longitude pair for $K$. Then the resultant manifold $M(K; 1/n)$ obtained by $1/n$-Dehn surgery on $K$ becomes a homology 3-sphere, and $\pi_1(M(K; 1/n)) \cong \pi_1(S^3 - K)/H$, where $H$ is the normal closure generated by $ml^n$ in $\pi_1(S^3 - K)$. Now let $L$ be the spun 2-knot of $K$. $\pi_1(S^4 - L) \cong \pi_1(S^3 - K)$. Let $C$ be an embedded circle in $S^4 - L$ representing $ml^n$ in $\pi_1(S^4 - L)$. Then the 2-knot $S$ constructed from $L$ and $C$ represents $\zeta$, and $\pi_1(S^2 \times S^2 - S) \cong \pi_1(M(K; 1/n))$. Thus we have

**Proposition 4.2.** *For every homology 3-sphere $M$ obtained by Dehn surgery, there exists a 2-knot in $S^2 \times S^2$ which represents $\zeta$ and whose group is isomorphic to $\pi_1(M)$.* □

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