FIBERED KNOTS WITH THE SAME 0-SURGERY AND THE SLICE-RIBBON CONJECTURE

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Abstract. Akbulut and Kirby conjectured that two knots with the same 0-surgery are concordant. In this paper, we prove that if the slice-ribbon conjecture is true, then the modified Akbulut-Kirby’s conjecture is false. We also give a fibered potential counterexample to the slice-ribbon conjecture.

1. Introduction

The slice-ribbon conjecture asks whether any slice knot in $S^3$ bounds a ribbon disk in the standard 4-ball $B^4$ ([19]). There are many studies on this conjecture (cf. [4, 5, 14, 23, 25, 27, 33, 34, 35]). On the other hand, until recently, few direct consequences of the slice-ribbon conjecture were known. This situation has been changed by Baker. He gave the following conjecture.

Conjecture 1.1 ([9, Conjecture 1]). Let $K_0$ and $K_1$ be fibered knots in $S^3$ supporting the tight contact structure. If $K_0$ and $K_1$ are concordant, then $K_0 = K_1$.

Baker proved a strong and direct consequence of the slice-ribbon conjecture as follows:

Theorem 1.2 ([9, Corollary 4]). If the slice-ribbon conjecture is true, then Conjecture 1.1 is true.

Originally, Conjecture 1.1 was motivated by Rudolph’s old question [50] which asks whether the set of algebraic knots is linearly independent in the knot concordance group. Here we observe the following, which was implicit in [9].

Observation 1.3. If Conjecture 1.1 is true, the set of prime fibered knots in $S^3$ supporting the tight contact structure is linearly independent in the knot concordance group (see Lemma 3.1). Moreover, the set of such knots contains algebraic knots (see Lemma 3.2). In this sense, Conjecture 1.1 is a generalization of Rudolph’s question. Therefore Theorem 1.2 implies that if the slice-ribbon conjecture is true, then the set of algebraic knots is linearly independent in the knot concordance group—an affirmative answer of Rudolph’s question.

Theorem 1.2 and Observation 1.3 make the slice-ribbon conjecture more important and fascinating.

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1 Conjecture 1.1 might be reformulated in terms of contact geometry, such as Legendrian knots and Lagrangian concordances, see [19]. We do not pursue in this direction.
In this paper, we give another consequence of the slice-ribbon conjecture. To state our main result, we recall Akbulut and Kirby’s conjecture on knot concordance in the Kirby’s problem list [31].

**Conjecture 1.4 (31 Problem 1.19).** If 0-surgeries on two knots give the same 3-manifold, then the knots are concordant.

Livingston [36] demonstrated a knot $K$ such that it is not concordant to $K^r$, where $K^r$ is the knot obtained from $K$ by reversing the orientation. Therefore Conjecture 1.4 is false since 0-surgeries on $K$ and $K^r$ give the same 3-manifold, however, the following conjecture seems to be still open.

**Conjecture 1.5.** If 0-surgeries on two knots give the same 3-manifold, then the knots with relevant orientations are concordant.

Note that Cochran, Franklin, Hedden and Horn [15] obtained a closely related result to Conjecture 1.5. Indeed they gave a negative answer to the following question: “If 0-surgeries on two knots are integral homology cobordant, preserving the homology class of the positive meridians, are the knots concordant?”

Our main result is the following.

**Theorem 1.6.** If the slice-ribbon conjecture is true, then Conjecture 1.5 is false.

In Section 2, we will prove Theorem 1.6. We outline the proof as follows: Let $K_0$ and $K_1$ be the unoriented knots depicted in Figure 1 and give arbitrary orientations on $K_0$ and $K_1$.

![Figure 1. The definitions of $K_0$ and $K_1$. Each rectangle labeled 1 implies a full twist.](image)

By using annular twisting techniques developed in [1, 2, 42, 53], we see that 0-surgeries on $K_0$ and $K_1$ give the same 3-manifold. On the other hand, by Miyazaki’s result [38], we can prove that $K_0#K_1^m$ is not ribbon, where $K_0#K_1^m$ denotes the connected sum of $K_0$ and the mirror image of $K_1$. Suppose that the slice-ribbon conjecture is true. Then $K_0#K_1^m$ is not slice. Equivalently, $K_0$ and $K_1$ are not concordant. As a summary, 0-surgeries on $K_0$ and $K_1$ give the same 3-manifold, however, they are not concordant if the slice-ribbon conjecture is true, implying that Conjecture 1.5 is false.

Here we consider the following question.
**Question 1.7.** Are the knots $K_0$ and $K_1$ in Figure 1 concordant?

This question is interesting since the proof of Theorem 1.6 tells us the following:

1. If $K_0$ and $K_1$ are concordant, then $K_0 \# \overline{K_1}$ is a counterexample to the slice-ribbon conjecture since $K_0 \# \overline{K_1}$ is not ribbon.

2. If $K_0$ and $K_1$ are not concordant, then Conjecture 1.5 is false since 0-surgeries on $K_0$ and $K_1$ give the same 3-manifold.

This paper is organized as follows: In Section 2 we prove Theorem 1.6. In Section 3, we consider consequences of Baker’s result in [9]. In Appendix A, we give a short review for Miyazaki’s in-depth study on ribbon fibered knots which is based on the theorem of Casson and Gordon [11]. In Appendix B, we recall twistings, annulus twists and annulus presentations. Moreover, we define annulus presentations compatible with fiber surfaces and study a relation between annulus twistings and fiberiness of knots. Finally, we describe monodromies of the fibered knots obtained from $6_3$ (with an annulus presentation) by annulus twistings.

**Notations.** Throughout this paper, we will work in the smooth category. Unless otherwise stated, we suppose that all knots are oriented. Let $K$ be a knot in $S^3$. We denote $M_K(0)$ the 3-manifold obtained from $S^3$ by 0-surgery on $K$ in $S^3$, and by $[K]$ the concordance class of $K$. For an oriented compact surface $F$ with a single boundary component and a diffeomorphism $f: F \to F$ fixing the boundary, we denote by $\hat{F}$ the closed surface $F \cup D^2$ and by $\hat{f}$ the extension $f \cup \text{id}: \hat{F} \to \hat{F}$. We denote by $t_C$ the right-handed Dehn twist along a simple closed curve $C$ on $F$.

**2. Proof of Theorem 1.6**

In this section, we prove our main theorem. The main tools are Miyazaki’s result [38, Theorem 5.5] and annular twisting techniques developed in [1, 2, 4, 2, 53]. For the sake of completeness, we will review these results in Appendices A and B.

**Proof of Theorem 1.6.** Let $K_0$ and $K_1$ be the unoriented knots as in Figure 1 and give arbitrary orientations on $K_0$ and $K_1$. By [1, Proposition 2.5] (or Lemma 5.6), 0-surgeries on $K_0$ and $K_1$ give the same 3-manifold (for detail, see Appendix B). In this case, $K_0$ admits an annulus presentation as in Figure 1 and $K_1 = A(K_0)$.

On the other hand, $K_0 \# \overline{K_1}$ is not a ribbon knot as follows: First, note that $K_0$ is the fibered knot $6_3$ in Rolfsen’s knot table, see KnotInfo [12]. By Gabai’s theorem in [20], $K_1$ is also fibered since 0-surgeries on $K_1$ and $K_2$ give the same 3-manifold (see also Remark 5.10). Therefore $K_0 \# \overline{K_1}$ is a fibered knot. Here we can see that $K_0$ and $K_1$ are different knots (for example, by calculating the Jones polynomials of $K_0$ and $K_1$). Also, we see that $K_0$ and $K_1$ have the same irreducible Alexander polynomial

$$\Delta_{K_0}(t) = \Delta_{K_1}(t) = 1 - 3t + 5t^2 - 3t^3 + t^4.$$  

By Miyazaki’s result [38, Theorem 5.5] (or Corollary 1.3), the knot $K_0 \# \overline{K_1}$ is not ribbon. Suppose that the slice-ribbon conjecture is true. Then $K_0 \# \overline{K_1}$ is not slice. Equivalently, $K_0$ and $K_1$ are not concordant. Therefore, if the slice-ribbon conjecture is true, then Conjecture 1.5 is false. \qed
3. Observations on Baker’s result

In this section, we consider consequences of Baker’s result in [9].

First, we recall some definitions. A fibered knot in \( S^3 \) is called tight if it supports the tight contact structure (see [9]). A set of knots is linearly independent in the knot concordance group if it is linearly independent in the knot concordance group as a \( \mathbb{Z} \)-module. We observe the following.

**Lemma 3.1.** If Conjectures [14] is true, then the set of prime tight fibered knots in \( S^3 \) is linearly independent in the knot concordance group.

**Proof.** Let \( K_1, K_2, \cdots, K_n \) be distinct prime tight fibered knots. Suppose that for some integers \( a_1, \ldots, a_n \) we have

\[
a_1[K_1] + \cdots + a_n[K_n] = 0.
\]

We will prove that if Conjectures [14] is true, then \( a_1 = a_2 = \cdots = a_n = 0 \). When \( a_1 \geq 0, \cdots, a_n \geq 0 \), then

\[
[(\#^{a_1}K_1)\# \cdots \#(\#^{a_n}K_n)] = 0.
\]

Note that \( (\#^{a_1}K_1)\# \cdots \#(\#^{a_n}K_n) \) is a tight fibered knot. If Conjectures [14] is true, then

\[
(\#^{a_1}K_1)\# \cdots \#(\#^{a_n}K_n)
\]

is the unknot. By the prime decomposition theorem of knots, we obtain

\[
a_1 = a_2 = \cdots = a_n = 0.
\]

When \( a_1 \leq 0, \cdots, a_n \leq 0 \), then

\[
[(\#^{-a_1}K_1)\# \cdots \#(\#^{-a_n}K_n)] = 0.
\]

By the same argument, we obtain

\[
a_1 = a_2 = \cdots = a_n = 0.
\]

For the other case, we may assume that \( a_1 \geq 0, \cdots, a_m \geq 0 \) and \( a_{m+1} \leq 0, \cdots, a_n \leq 0 \) by changing the order of the knots. Then we obtain

\[
a_1[K_1] + \cdots + a_m[K_m] = (-a_{m+1})[K_{m+1}] + \cdots + (-a_n)[K_n].
\]

Equivalently,

\[
[(\#^{a_1}K_1)\# \cdots \#(\#^{a_m}K_m)] = [(\#^{-a_{m+1}}K_{m+1})\# \cdots \#(\#^{-a_n}K_n)].
\]

Note that \( (\#^{a_1}K_1)\# \cdots \#(\#^{a_m}K_m) \) and \( (\#^{-a_{m+1}}K_{m+1})\# \cdots \#(\#^{-a_n}K_n) \) are tight fibered knots. If Conjectures [14] is true, then

\[
(\#^{a_1}K_1)\# \cdots \#(\#^{a_m}K_m) = (\#^{-a_{m+1}}K_{m+1})\# \cdots \#(\#^{-a_n}K_n).
\]

By the prime decomposition theorem of knots, we obtain

\[
a_1 = a_2 = \cdots = a_n = 0.
\]

□

Lemma 3.1 leads us to ask which knots are (prime) tight fibered. Recall that algebraic knots are links of isolated singularities of complex curves and \( L \)-space knots are those admitting positive Dehn surgeries to \( L \)-spaces.

\[\text{In our definition, the left-handed trefoil is not an } L \text{-space knot. Note that some authors define } L \text{-space knots to be those admitting non-trivial Dehn surgeries to } L \text{-spaces. In this definition, the left-handed trefoil is an } L \text{-space knot.}\]
Lemma 3.2. We have the following.

1. A fibered knot is tight if and only if it is strongly quasipositive.
2. An algebraic knot is a prime tight fibered knot.
3. An L-space knot is a prime tight fibered knot.
4. A divide knot is a tight fibered knot.
5. A positive fibered knot is a tight fibered knot.
6. An almost positive fibered knot is a tight fibered knot.

Proof. (1) This follows from [26, Proposition 2.1] (see also [8]).

(2) It is well known that any algebraic knot is fibered and strongly quasipositive. By (1), it is tight fibered. In fact, any algebraic knot is an iterated cable of a torus knot. This implies that it is prime. For the details on algebraic knots, see [17], [28], [54].

(3) By [40, 41] (see also [21], [45]), an L-space knot is fibered. Hedden [26] proved that it is tight. It is also known that an L-space knot is prime, see [32].

(4) A’Campo [6, 7] defined divide knots and proved that they are fibered. Kawa-
mura [30] proved that any divide knot is quasipositive. Moreover, she computed the four-ball genus $g_4(K)$ of a divide knot $K$ and we see that it is equal to the genus $g_3(K)$ of the knot (see also [29]). It is known that $\tau(K) = g_4(K)$ for any quasipositive knot $K$ (see [37, Corollary 2]), where $\tau(K)$ is Ozsváth and Szabó’s $\tau$-invariant of $K$ [34] and [49]. Hence, any divide knot is a fibered knot with $\tau(K) = g_3(K)$. By [26, Proposition 2.1], such a fibered knot is tight.

(5) Nakamura [39] and Rudolph [51] proved that any positive knot is strongly quasipositive. By (1), a positive fibered knot is tight.

(6) The authors [3] proved that any almost positive fibered knot is strongly quasi-
positive. By (1), an almost positive fibered knot is tight. □

Remark 3.3. By Theorem 1.2 and Lemmas 3.1 and 3.2, if the slice-ribbon con-
jecture is true, then the set of L-space knots in $S^3$ is also linearly independent in the knot concordance group.

The following conjecture may be manageable than Conjecture 1.1

Conjecture 3.4. The set of L-space knots in $S^3$ is linearly independent in the knot concordance group. In particular, if L-space knots $K_0$ and $K_1$ are concordant, then $K_0 = K_1$.

4. Appendix A: Miyazaki’s results on ribbon fibered knots

In this appendix, we recall Miyazaki’s results [38] on non-simple ribbon fibered knots, in particular, on composite ribbon fibered knots.

Let $K_i$ be a knot in a homology 3-sphere $M_i$ for $i = 0, 1$. We write

$$(M_1, K_1) \geq (M_0, K_0) \text{ (or simply } K_1 \geq K_0)$$

if there exist a 4-manifold $X$ with $H_s(X, \mathbb{Z}) \simeq H_s(S^3 \times I, \mathbb{Z})$ and an annulus $A$ embedded into $X$ such that

$$\partial X, A \cap \partial X = (M_1, K_1) \cup (M_0^r, K_0^r),$$

$$\pi_1(M_1 \setminus K_1) \to \pi_1(X \setminus A) \text{ is surjective, and }$$

$$\pi_1(M_0 \setminus K_0) \to \pi_1(X \setminus A) \text{ is injective},$$

where $(M_0^r, K_0^r)$ is $(M_0, K_0)$ with reversed orientation. We say $K_1$ is homotopically ribbon concordant to $K_0$ if $K_1 \geq K_0$. Note that this is a generalization of the
notion of “ribbon concordant”, see in [24, Lemma 3.4]. A knot $K$ in a homotopy 3-sphere $M$ is homotopically ribbon if $K \geq U$, where $U$ is the unknot in $S^3$. A typical example of a homotopically ribbon knot is a ribbon knot in $S^3$ (for detail see [38, p.3]).

**Theorem 4.1** ([38, Theorem 5.5]). For $i = 1, \ldots, n$, let $K_i$ be a prime fibered knot in a homotopy 3-sphere $M_i$ satisfying one of the following:

- $K_i$ is minimal with respect to “$\geq$” among all fibered knots in homology spheres,
- there is no $f(t) \in \mathbb{Z}[t] \setminus \{\pm t^k\}$ such that $f(t)f(t^{-1})|\Delta_{K_i}(t)$.

If $K_1 \# \cdots \# K_n$ is homotopically ribbon, then the set \{1, \ldots, n\} can be paired into \(\sqcup_{s=1}^m \{i_s, j_s\}\) such that $K_{i_s} = \overline{K_{j_s}}$, where $\overline{K_{j_s}}$ is $(M_{j_s}^r, K_{j_s})$.

**Remark 4.2.** By a solution of the geometrization conjecture (see [46, 47] and [48]), each homotopy 3-sphere $M_i$ is $S^3$ in the above theorem.

As a corollary, we obtain the following.

**Corollary 4.3.** Let $K_0$ and $K_1$ be fibered knots in $S^3$ with irreducible Alexander polynomials. If $K_0 \# K_1$ is ribbon, then $K_0 = K_1$.

5. **Appendix B: Twistings, Annulus twists and Annulus presentations**

In this appendix, we recall two operations. One is twisting, and the other is annulus twist [1]. In a certain case, annulus twists are expressed in terms of twistings and preserve some properties of knots. Finally, we describe monodromies of the fibered knots obtained from $6_3$ (with an annulus presentation) by annulus twists.

We begin this appendix with recalling the definition of an open book decomposition of a 3-manifold.

5.1. **Open book decompositions.** Let $F$ be an oriented surface with boundary and $f : F \to F$ a diffeomorphism on $F$ fixing the boundary. Consider the pinched mapping torus

$$\widehat{M}_f = F \times [0,1]/\sim,$$

where the equivalent relation $\sim$ is defined as follows:

1. $(x,1) \sim (f(x),0)$ for $x \in F$, and
2. $(x,t) \sim (x,t')$ for $x \in \partial F$ and $t, t' \in [0,1]$.

Here, we orient $[0,1]$ from 0 to 1 and we give an orientation of $\widehat{M}_f$ by the orientations of $F$ and $[0,1]$. Let $M$ be a closed oriented 3-manifold. If there exists an orientation-preserving diffeomorphism from $\widehat{M}_f$ to $M$, the pair $(F,f)$ is called an open book decomposition of $M$. The map $f$ is called the monodromy of $(F,f)$. Note that we can regard $F$ as a surface in $M$. The boundary of $F$ in $M$, denoted by $L$, is called a fibered link in $M$, and $F$ is called a fiber surface of $L$. The monodromy of $L$ is defined by the monodromy $f$ of the open book decomposition $(F,f)$.

5.2. **Twistings and annulus twists.** Let $M$ be a closed oriented 3-manifold, and $(F,f)$ an open book decomposition of $M$. Let $C$ be a simple closed curve on a fiber surface $F \subset M$. Then, twisting along $C$ of order $n$ is defined as performing $(1/n)$-surgery along $C$ with respect to the framing determined by $F$. Then we obtain the following.
Lemma 5.1 (Stallings). The resulting manifold obtained from $M$ by twisting along $C$ of order $n$ is (orientation-preservingly) diffeomorphic to $\tilde{M}_{C,n}\circ f$.

For a proof of this lemma, see Figure 2 (see also [10], [13] and [52]). Lemma 5.1 implies that, by twisting along $C$ of order $n$, the fibered link with monodromy $f$ is changed into the fibered link with monodromy $t_C^n \circ f$.

Remark 5.2. Our definition on the pinched mapping torus differs from Bonahon’s [10]. We glue $(x,1)$ and $(f(x),0)$ in the pinched mapping torus. On the other hand, $(x,0)$ and $(f(x),1)$ are glued in Bonahon’s paper.

Hereafter we only deal with the 3-sphere $S^3$. Let $A \subset S^3$ be an embedded annulus and $\partial A = c_1 \cup c_2$. Note that $A$ may be knotted and twisted. In Figure 3 we draw an unknotted and twisted annulus. An $n$-fold annulus twist along $A$ is to apply $(+1/n)$-surgery along $c_1$ and $(-1/n)$-surgery along $c_2$ with respect to the framing determined by the annulus $A$. For simplicity, we call a 1-fold annulus twist along $A$ an annulus twist along $A$.

Remark 5.3. An $n$-fold annulus twist does not change the ambient 3-manifold $S^3$, (see [3] Lemma 2.1) or [42] Theorem 2.1). However, each surgery along $c_1$ (resp. surgery along $c_2$) often changes the ambient 3-manifold $S^3$. For example, if $A$ is an unknotted annulus with $k$ full-twists, the $n$-fold annulus twist along $A$ is to apply $(k+1/n)$-surgery along $c_1$ and $(k-1/n)$-surgery along $c_2$ with respect to the Seifert framings. Therefore each surgery along $c_1$ (resp. surgery along $c_2$) indeed changes the ambient 3-manifold $S^3$ frequently.

5.3. Annulus presentations. The first author, Jong, Omae and Takeuchi [1] introduced the notion of an annulus presentation of a knot (in their paper it is called “band presentation”). Here, we extend the definition of annulus presentations of knots.

Let $A \subset S^3$ be an embedded annulus with $\partial A = c_1 \cup c_2$, which may be knotted and twisted. Take an embedding of a band $b : I \times I \to S^3$ such that
\[
\begin{align*}
\bullet & \quad b(I \times I) \cap \partial A = b(\partial I \times I), \\
\bullet & \quad b(I \times I) \cap \text{int } A \text{ consists of ribbon singularities, and} \\
\bullet & \quad A \cup b(I \times I) \text{ is an immersion of an orientable surface,}
\end{align*}
\]
where $I = [0,1]$. If a knot $K$ is isotopic to the knot $(\partial A \setminus b(\partial I \times I)) \cup b(I \times \partial I)$, then we say that $K$ admits an annulus presentation $(A,b)$.

Example 5.4. The knot 6₃ (with an arbitrary orientation) admits an annulus presentation $(A,b)$, see Figure 4.

Let $K$ be a knot admitting an annulus presentation $(A,b)$. Then, by $A^n(K)$, we denote the knot obtained from $K$ by $n$-fold annulus twist along $A$ with $\partial \tilde{A} = \tilde{c}_1 \cup \tilde{c}_2$, where $\tilde{A} \subset A$ is a shrunken annulus. Namely, $\overline{A \setminus A}$ is a disjoint union of two annuli, each $\tilde{c}_i$ is isotopic to $c_i$ in $\overline{A \setminus A}$ for $i = 1, 2$ and $\overline{A \setminus (\partial A \cup \tilde{A})}$ does not intersect $b(I \times I)$. For simplicity, we denote $A^1(K)$ by $A(K)$.

Example 5.5. We consider the knot 6₃ with the annulus presentation $(A,b)$ in Figure 4. Then $A(6₃)$ is the right picture in Figure 4.

An important result which was first proved by Osinach is the following (though he did not use the notion of an annulus presentation).
Lemma 5.6 ([1, Proposition 2.5], [42]). Let $K$ be a knot admitting an annulus presentation $(A, b)$. Then, the 3-manifold $M_{A^n(K)}(0)$ does not depend on $n \in \mathbb{Z}$.
**Figure 3.** An unknotted annulus $A \subset S^3$ with $+1$ full-twist.

**Figure 4.** The definitions of the knot $6_3$ (left) and its annulus presentation (right).

**Figure 5.** A shrunken annulus $\tilde{A}$ for the annulus presentation of $6_3$ (left) and the knot $A(6_3)$ (right).

**Remark 5.7.** When the first author, Jong, Omae and Takeuchi defined annulus twists and annulus presentations, they assumed that the annuli (in the definitions of annulus twists and annulus presentations) are unknotted and the number of twistings of each annulus is $+1$ or $-1$ (that is, the Hopf band), see [1]. Originally, Lemma 5.6.
was proved for annulus presentations (in the sense of [1]), however, we can prove it for annulus presentations (in the sense of this paper) by the same discussion in [1].

5.4. Compatible annulus presentations and twistings. Let $K \subset S^3$ be a fibered knot admitting an annulus presentation $(A, b)$, and $F$ a fiber surface of $K$. We say that $(A, b)$ is compatible with $F$ if there exist simple closed curves $c'_1$ and $c'_2$ on $F$ such that

- $\partial A = \tilde{c}_1 \cup \tilde{c}_2$ is isotopic to $c'_1 \cup c'_2$ in $S^3 \setminus K$, where $\tilde{A} \subset A$ is a shrunken annulus defined in Section 5.3 and each annular neighborhood of $c'_i$ in $F$ ($i = 1, 2$) is isotopic to $A$ in $S^3$.

Let $\tilde{c}_1 \cup \tilde{c}_2$ be the framed link with framing $(1/n, -1/n)$ with respect to the framing determined by the annulus $A$, and $c'_1 \cup c'_2$ the framed link with framing $(1/n, -1/n)$ with respect to the framing determined by the fiber surface $F$. Then, by the first compatible condition, $\tilde{c}_1 \cup \tilde{c}_2$ is equal to $c'_1 \cup c'_2$ as links in $S^3 \setminus K$. Moreover, by the second compatible condition, their framings coincide. As a result, $\tilde{c}_1 \cup \tilde{c}_2$ is equal to $c'_1 \cup c'_2$ as framed links in $S^3 \setminus K$. Hence, if $K$ is a fibered knot with $(A, b)$ which is compatible with the fiber surface $F$, then $A^n(K)$ is the knot obtained from $K$ by twisting along $c'_1$ and $c'_2$ of order $+n$ and $-n$, respectively. In particular, $A^n(K)$ is a fibered knot and the monodromy of $A^n(K)$ is $t_{c'_1}^{-n} \circ t_{c'_2}^n \circ f$, where $f$ is the monodromy of $K$. As a summary, we obtain the following.

**Lemma 5.8.** Let $K \subset S^3$ be a fibered knot admitting an annulus presentation $(A, b)$. Then $A^n(K)$ is also fibered for any $n \in \mathbb{Z}$. Moreover, if the annulus presentation is compatible with the fiber surface, the monodromy of $A^n(K)$ is

$$t_{c'_1}^{-n} \circ t_{c'_2}^n \circ f,$$

where $f$ is the monodromy of $K$, and $c'_1$ and $c'_2$ are simple closed curves which give the compatibility of $(A, b)$.

**Example 5.9.** We consider the knot $6_3$ with the annulus presentation $(A, b)$ in Figure 4. It is known that $6_3$ is fibered. We choose a fiber surface as in left picture in Figure 6 and denote it by $F$. In this case, the annulus presentation $(A, b)$ is compatible with $F$. Indeed we define simple closed curves $c'_1$ and $c'_2$ on $F$ by $\tilde{c}_1$ and $\tilde{c}_2$, where $\partial \tilde{A} = \tilde{c}_1 \cup \tilde{c}_2$. Then $c'_1 \cup c'_2$ clearly satisfies the compatible conditions.

\[\text{Figure 6. A fiber surface } F \text{ of } 6_3 \text{ (left) and a shrunken annulus } \tilde{A} \text{ (center). The annulus presentation } (A, b) \text{ of } 6_3 \text{ is compatible with the fiber surface } F \text{ (right).}\]
Remark 5.10. Let $K_1$ and $K_2$ be knots which have the same 0-surgery. Gabai [20] proved that if $K_1$ is fibered, then $K_2$ is also fibered. Here let $K$ be a fibered knot admitting an annulus presentation $(A, b)$ (may not be compatible with the fiber surface for $K$). Then, by Lemma 5.6 and the above fact (Gabai’s theorem), $A^n(K)$ is also fibered.

5.5. The monodromy of $A^n(6_3)$. At first, we describe the monodromy of $6_3$. We draw a fiber surface of $6_3$ as a plumbing of some Hopf bands (see Figure 7). From Figures 8 and 9, the monodromy of $6_3$ is given by $t_d^{-1} \circ t_b \circ t_c^{-1} \circ t_a$.

Now we describe the monodromy of $A^n(6_3)$. From Figures 8 and Lemma 5.8 the monodromy $f_n$ of $A^n(6_3)$ is given by $t_{c_1}^{-n} \circ t_{c_2}^{-n} \circ t_d^{-1} \circ t_b \circ t_c^{-1} \circ t_a$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{The bottom right pictures are fiber surfaces of $6_3$ given by a plumbing of some Hopf bands. The loops $a$, $b$, $c$ and $d$ are core lines of these Hopf bands.}
\end{figure}

Let $K_n$ be the fibered knot $A^n(6_3)$. Then the closed monodromies $\hat{f}_n$ are conjugate with each other. It follows from two facts:

1. 0-surgeries on $K_n$ are the same 3-manifold (which is the surface bundle over $S^1$ with monodromy $\hat{f}_n$ and whose first Betti number is one).
2. The monodromy of any surface bundle over $S^1$ with first Betti number one is unique up to conjugation.

Hence, the closed monodromies $\hat{f}_n$ do not distinguish the knots $K_n$. On the other hand, we see that the monodromies $f_n$ distinguish the knots $K_n$ by Remark 5.11 below.
Figure 8. The simple closed curves $c'_1$ and $c'_2$ on the fiber surface of $6_3$.

Figure 9. The monodromy $f_n$ of $A^n(6_3)$ is $t_{c_2}^{-n} \circ t_{c_1}^{-n} \circ t_d^{-1} \circ t_b \circ t_c^{-1} \circ t_a$. This is equal to $t_a^{-1} \circ t_b^{-1} \circ t_c^{-1} \circ t_{c_1}^{-1} \circ t_b \circ t_c^{-1} \circ t_d^{-1} \circ t_b \circ t_c^{-1} \circ t_a$, where $e$ is the circle depicted in this picture.

Remark 5.11. Let $\xi_n$ be the contact structure on $S^3$ supported by the open book decomposition $(F, f_n)$. Oba told us that

$$d_3(\xi_n) = -n^2 - n + \frac{3}{2},$$

where $d_3$ is the invariant of plane fields given by Gompf [22]. In order to compute $d_3(\xi_n)$, he used the formula for $d_3$ introduced in [16] [18]. By this computation, if $K_n$ and $K_m$ are the same fibered knots, then $n = m$ or $n + m = -1$. Moreover if $n + m = -1$, we can check that $K_n$ and $K_m$ are the same fibered knots. As a result, we see that $K_n$ and $K_m$ are the same fibered knots if and only if $n = m$ or $n + m = -1$. In particular, knots $K_n$ ($n \geq 0$) are mutually distinct.
For a knot $K$ with an annulus presentation $(A, b)$, in general, it is hard to distinguish $A^n(K)$ and $A^m(K)$. Indeed, they have the same Alexander modules. Oosinach \cite{Oosinach2013} and Teragaito \cite{Teragaito2013} used the hyperbolic structure of the complement of $A^n(K)$ to solve the problem (more precisely, they considered the hyperbolic volume of $A^n(K_n)$). On the other hand, in Oba’s method, we consider contact structures.

**Remark 5.12.** In the proof of Theorem 1.6, we proved that $K_0\# K_1$ is not ribbon. By the same discussion, if $K_n \neq K_m$, we also see that $K_n\# K_m$ is not ribbon and it is a counterexample for either Conjecture 1.3 or the slice-ribbon conjecture. In particular, by Remark 5.11, we obtain infinitely many fibered potential counterexamples to the slice-ribbon conjecture by utilizing annulus twists.

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**References**

[1] T. Abe, I. Jong, Y. Omae and M. Takeuchi, *Annulus twist and diffeomorphic 4-manifolds*, Math. Proc. Cambridge Philos. Soc. 155 (2013), No. 2, 219–235.

[2] T. Abe, I. Jong, J. Luecke and J. Oosinach, *Infinitely many knots admitting the same integer surgery and a 4-dimensional extension*, to appear in Int. Math. Res. Not. IMRN.

[3] T. Abe and K. Tagami, *Characterization of positive links and the s-invariant for links*, arXiv:1405.4061 (2014).

[4] T. Abe and M. Tange, *Omae’s knot and 12₄₉₉₀ are ribbon*, RIMS Kôkyûroku 1812 (2012), 34–42.

[5] T. Abe and M. Tange, *A construction of slice knots via annulus twists*, arXiv:1305.4492 (2013).

[6] N. A’Campo, *Generic immersion of curves, knots, monodromy and gordian number*, Publ. Math. I.H.E.S. 88 (1998), 151–169.

[7] N. A’Campo, *Real deformations and complex topology of plane curve singularities*, Ann. Fac. Sci. Toulouse 8 (1999), 5–23.

[8] S. Baader and M. Ishikawa, *Legendrian graphs and quasipositive diagrams*, Ann. Fac. Sci. Toulouse Math. (6) 18 (2009), no. 2, 285–305.

[9] K. L. Baker, *A note on the concordance of fibered knots*, arXiv:1409.7646 (2014).

[10] F. Bonahon, *Ribbon fibred knots, cobordism of surface diffeomorphisms and pseudo-Anosov diffeomorphisms*, Math. Proc. Cambridge Philos. Soc. 94 (1983), no. 2, 235–251.

[11] A. J. Casson and C. McA. Gordon, *A loop theorem for duality spaces and fibre ribbon knots*, Invent. Math. 74 (1983), no. 1, 119–137.

[12] J. C. Cha and C. Livingston, *KnotInfo: Table of Knot Invariants*, http://www.indiana.edu/~knotinfo today’s date (e.g. September 30, 2014).

[13] B. Chantraine, *Lagrangian concordance of Legendrian knots*, Algebr. Geom. Topol. 10 (2010), 63–85.

[14] T. Cochran and C. Davis, *Counterexamples to Kauffman’s conjectures on slice knots*, to appear in Advances in Math.

[15] T. D. Cochran, B. D. Franklin, M. Hedden and P. D. Horn, *Knot concordance and homology cobordism*, Proc. Amer. Math. Soc. 141 (2013), No. 6, 2193–2208.

[16] F. Ding, H. Geiges, A. I. Stipsicz, *Surgery diagrams for contact 3-manifolds*. Turkish J. Math. 28 (2004), no. 1, 41–74.

[17] D. Eisenbud and W. D. Neumann, *Three-dimensional link theory and invariants of plane curve singularities*, Ann. Math. Stud. 110. Princeton. Princeton Univ. Press (1985).

[18] J. Etnyre, B. Ozbagci, *Invariants of contact structures from open books*. Trans. Amer. Math. Soc. 360 (2008), no. 6, 3133–3151.
[19] R. H. Fox, *Some problems in knot theory*, Topology of 3-manifolds and related topics (Proc. The Univ. of Georgia Institute), (1962), 168–176.
[20] D. Gabai, *Foliations and the topology of 3-manifolds. III*, J. Diff. Geom. **26** (1987), No. 3, 479–536.
[21] P. Ghiggini, *Knot Floer homology detects genus-one fibred knots*, Amer. J. Math. **130** (2008), No. 5, 1151–1169.
[22] R. Gompf, *Handlebody construction of Stein surfaces*. Ann. of Math. (2) **148** (1998), no. 2, 619–693.
[23] R. Gompf, M. Scharlemann and A. Thompson, *Fibered knots and potential counterexamples to the property 2R and slice-ribbon conjectures*, Geom. Topol. **14** (2010), no. 4, 2305–2347.
[24] C. McA. Gordon, *Ribbon concordance of knots in the 3-sphere*, Math. Ann. **257** (1981), no. 2, 157–170.
[25] J. Greene and S. Jubuka, *The slice-ribbon conjecture for 3-strand pretzel knots*, Amer. J. Math. **133** (2011), no. 3, 555–580.
[26] M. Hedden, *Notions of positivity and the Ozsváth-Szabó concordance invariant*, J. Knot Theory Ramifications **19** (2010), no. 5, 617–629.
[27] M. Hedden, P. Kirk and C. Livingston, *Non-slice linear combinations of algebraic knots*, J. Eur. Math. Soc. (JEMS) **14** (2012), no. 4, 1181–1208.
[28] J. Hillman, *Algebraic Invariants of links*, Series on Knots and Everything vol. **32**, World Scientific, New Jersey-London-Singapore-Hong Kong, 2002.
[29] T. Kawamura, *Visualization of A’Campo’s fibered links and unknotting operations*, Topology Appl. **121** (2002), no. 1, 287–304.
[30] R. Kirby, *Problems in low-dimensional topology*, AMS/IP Stud. Adv. Math. **2** (2), Geometric topology (Athens, GA, 1993), 35–473 (Amer. Math. Soc. 1997).
[31] P. Lisca, *Lens spaces, rational balls and the ribbon conjecture*, Geom. Topol. **11** (2007), no. 1, 111–123.
[32] C. Livingston, *Knots which are not concordant to their reverses*, Quart. J. Math. Oxford Ser. (2) **34** (1983), no. 135, 323–328.
[33] C. Livingston, *Computations of the Ozsváth-Szabó knot concordance invariant*, Geom. Topol. **8** (2004), 735–742.
[34] T. Nakamura, *Four-genus and unknotting number of positive knots and links*, Osaka J. Math. **37** (2000), no. 2, 441–451.
[35] Y. Ni, *Knot Floer homology detects fibred knots*, Invent. Math. **170** (2007), No. 3, 577–608.
[36] Y. Ni, *Erratum: Knot Floer homology detects fibred knots*, Invent. Math. **177** (2009), No. 1, 235–238.
[37] J. Osoinach, *Manifolds obtained by surgery on an infinite number of knots in S^3*, Topology **45** (2006), no. 4, 725–733.
[38] B. Ozbagci and A. I. Stipsicz, *Surgery on contact 3-manifolds and Stein surfaces*, Bolyai Society Mathematical Studies **13**, Springer-Verlag, Berlin; János Bolyai Mathematical Society, Budapest, 2004.
[39] P. S. Ozsváth and Z. Szabó, *Knot Floer homology and the four-ball genus*, Geom. Topol. **7** (2003), 615–639.
[40] P. S. Ozsváth and Z. Szabó, *On knot Floer homology and lens space surgeries*, Topology, **44** (2005), no. 6, 1281–1300.
[41] G. Perelman, *The entropy formula for the Ricci flow and its geometric applications*, arXiv:math/0211159 (2002).
[42] G. Perelman, *Finite extinction time for the solutions to the Ricci flow on certain three-manifolds*, arXiv:math/0307245 (2003).
[43] G. Perelman, *Ricci flow with surgery on three-manifolds*, arXiv:math/0303109 (2003).
[49] J. Rasmussen, *Floer homology and knot complements*, ProQuest LLC, Ann Arbor, MI, 2003, Thesis (Ph.D.) Harvard University.

[50] L Rudolph, *How independent are the knot-cobordism classes of links of plane curve singularities?*, Notices Amer. Math. Soc. **23** (1976), 410.

[51] L. Rudolph, *Constructions of quasipositive knots and links. I*, Knots, braids and singularities (Plains-sur-Bex, 1982), Monogr. Enseign. Math., vol. **31**, Enseignement Math., Geneva, 1983, 233–245.

[52] J. Stallings, *Constructions of fibred knots and links*, Proc. Sympos. Pure Math. 32, part 2 (1978), 55–60.

[53] M. Teragaito, *A Seifert fibered manifold with infinitely many knot-surgery descriptions*, Int. Math. Res. Not. IMRN **9** (2007), Art. ID rnm 028, 16.

[54] C. T. C. Wall, *Singular points of plane curves*, London Mathematical Society Student Texts **63**, Cambridge University Press, Cambridge, 2004.

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