THE HEEGAARD GENUS OF BUNDLES OVER S^1

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1. INTRODUCTION

This is a largely expository paper exploring theorems of Rubinstein and Lackenby. Rubinstein's Theorem studies the Heegaard genus of certain hyperbolic 3-manifolds that fiber over S^1 and Lackenby's Theorem studies the Heegaard genus of certain Haken manifolds. Our target audience are 3-manifold theorists with good understanding of Heegaard splittings but perhaps little experience with minimal surfaces. The main purpose of this note is generalizing Rubinstein's minimal surface argument (Section 4) and explaining the minimal surface technology necessary for that theorem (Section 3).

We assume familiarity with the basic notions of 3-manifold theory (*e.g* [4][6]), the basic nations about Heegaard splittings (*e.g.* [13]), and Casson–Gordon's [1] concept of *strong irreducibility/weak reducibility*. In Section 5 we assume familiarity with Scharlemann–Thompson untelescoping. All manifolds considered in this paper are closed, orientable 3-manifolds and all surfaces considered are closed and orientable. By the genus of a 3-manifold M (denoted $g(M)$) we mean the genus of a minimal genus Heegaard surface for M.

In [12] Rubinstein used minimal surfaces to study the Heegaard genus of hyperbolic manifolds that fiber over S^1, more precisely, of closed 3-manifolds (say M_ϕ or simply M when there is no place for confusion) that fiber over the circle with fiber a closed surface of genus g and pseudo-Anosov monodromy (say ϕ). While there exist genus two manifolds that fiber over S^1 with fiber of arbitrarily high genus (for example, consider 0-surgery on 2 bridge knots with fibered exterior [3]) Rubinstein showed that this is often not the case: a manifold that fibers over S^1 with genus g fiber has a Heegaard surface of genus $2g + 1$ that is obtained by taking two disjoint fibers and tubing them together once on each side. We call this surface and surfaces obtained by stabilizing it *standard*. M has a cyclic cover of degree d (denoted M_{ϕ^d} or simply M_d), dual to the fiber, whose monodromy is ϕ^d. Rubinstein shows that for small h and large d any Heegaard surface for M_d of genus $\leq h$ is a stabilization of the standard Heegaard surface of

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M_d. In particular, the Heegaard genus of M_d (for sufficiently large d) is $2g + 1$. The precise statement of Rubinstein's Theorem is:

Theorem 1.1 (Rubinstein)**.** *Let M be a bundle over S^1 with pseudo-Anosov monodromy ϕ. Then for any integer $h \geq 0$ there exists a constant n so that for any $d \geq n$, any Heegaard surface of genus $\leq h$ for M_d is standard.*

Rubinstein's proof contains two components: the first component is a reduction to a statement about minimal surfaces (given, for completeness, in Section 2). It says that if M_d has the property that every minimal surface of genus $\leq h$ is homotopic into a fiber then every Heegaard surface for M_d of genus $\leq h$ is standard. The second component is showing that for large enough d, this property holds for M_d. In Section 4 we generalize the second component; we now describe the generalization.

Let M be a hyperbolic manifold and $F \subset M$ a non-separating surface (not necessarily a fiber in a fibration over S^1). Construct the d-fold cyclic covers dual to F, denoted M_d, as follows: let M^* be M cut open along F. Then ∂M^* has two components, say F_- and F_+. The identification of F_- with F_+ in M defines a homeomorphism $h : F_- \to F_+$. We take d copies of M^* (denoted M_i^*, with boundaries denoted $F_{i,-}$ and $F_{i,+}$ ($i = 1, \ldots, d$)) and glue them together by identifying $F_{i,+}$ with $F_{i+1,-}$ (the indices are taken modulo d). The gluing maps are defined using h. The manifold obtained is M_d. In Theorem 4.1 we prove that for any M there exists n so that if $d \geq n$ then any minimal surface of genus $\leq h$ in M_d is disjoint from at least one of the preimages of F. If F is a fiber in a fibration over S^1, we see that any minimal surface of genus $\leq h$ is disjoint from a fiber, and hence homotopic into a fiber, as required.

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As in Rubinstein's original proof, our argument is based on an area estimate. Let S be a minimal surface in some hyperbolic manifold M as above. We give a lower bound on the area of a minimal surface (say S) in M_d that intersects every preimage of F by showing that there is a constant $a > 0$ so that S has area at least a near every preimage of F. Hence if S intersects every fiber it has area at least ad. Fixing h, if $d > \frac{2\pi(2h-2)}{a}$ then S has area $> 2\pi(2h-2)$. Since the minimal surface S inherits a metric with curvature ≤ -1, by Gauss–Bonnet it has area $\leq 2\pi(2g(S) - 2)$. Thus $g(S) > h$ as required. We note that a depends only on the geometry of M.

The only tool needed for this is a simple consequence of the *monotonicity formula*. It says that any minimal surface in a hyperbolic ball of radius R that intersects the center of the ball has at least as much area as a hyperbolic disk of radius R. We briefly explain this in Section 3. For the purpose of illustration give two proofs in the case that the minimal surface is a disk. One of the proofs requires the following fact: the length of a curve of a sphere that intersects every great is at least $2\pi r$, that is, such curve cannot be shorter than a great circle. We give two proofs of this fact in Appendices A and B.

Let N_1 and N_2 be hyperbolic manifolds with $\partial N_1 \cong \partial N_2$ a connected surface of genus $g \geq 2$ (denoted S_g). After fixing parameterizations $i_1 : S_g \to \partial N_1$ and $i_2 : S_g \to \partial N_2$ any gluing between ∂N_1 and ∂N_2 is given by a map $i_2 \circ f \circ (i_1^{-1})$ for some map $f : S_g \to S_g$. Fix $f : S_g \to S_g$ a pseudo-Anosov map, let M_f be the bundle over S^1 with fiber S_g and monodromy f, and M_∞ the infinite cyclic cover of M_f dual to the fiber. For $n \in \mathbb{N}$, let M_n be the manifold obtained by gluing N_1 to N_2 using the map $i_2 \circ f^n \circ (i_1^{-1})$. (Note that this is *not* M_d.) Soma [19] showed that for properly chosen points $x_n \in M_n$, (M_n, x_n) converge geometrically (in the Hausdorff–Gromov sense) to M_∞. In [9] Lackenby uses an area argument to show that for fixed h and sufficiently large n every minimal surface of genus $\leq h$ in M_n is disjoint from the image of $\partial N_1 = \partial N_2$ (denoted S). This implies that any Heegaard surface of genus $\leq h$ weakly reduces to S, and in particular for sufficiently large n, by [17] $g(M_n) = g(N_1) + g(N_2) - g(S)$. In Section 5 we discuss Lackenby's Theorem, following the same philosophy we used for Theorem 1.1. Finally we mention Souto's far reaching generalization of Lackenby's Theorem [20]; however, the proof of this theorem is beyond the scope of this note.

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2. Reduction of minimal surfaces

In this section we reduce Theorem 1.1 to a statement about minimal surfaces in M_d. We note that the result here applies to any hyperbolic bundle M, but for consistency with applications below we use the notation M_d.

Theorem 2.1 (Rubinstein)**.** *Let M_d be a hyperbolic bundle over S^1. Assume that every minimal surface of genus $\leq h$ in M_d is homotopic into a fiber. Then any Heegaard surface of genus $\leq h$ for M_d is a stabilization of the standard Heegaard surface.*

Sketch of proof. This proof is taken directly out of Rubinstein and for completeness we sketch it here. Assume first that M admits a strongly irreducible Heegaard surface of genus $\leq h$, say Σ. Then by Pitts and Rubinstein [11] Σ is isotopic to a minimal surface. Since Σ carries the fundamental group of M_d it is not homotopic into a fiber, contradicting our assumptions.

Next assume that M admits a weakly reducible Heegaard surface of genus $\leq h$, say Σ. By Casson and Gordon [1] a carefully chosen weak reduction of Σ yields a (perhaps disconnected) essential surface F, and every component of F has genus less than the $g(\Sigma)$ (and hence $< h$). By [16] (see also [2]) F is homotopic to a least area (and hence minimal) representative. By assumption F is homotopic into a fiber, and in particular F is embedded in fiber cross $[0, 1]$. Hence F is itself a collection of fibers and Σ is obtained from F by tubing. It is left as an exercise to show that [14] implies that Σ is standard. □

3. THE MONOTONICITY PRINCIPLE

The Monotonicity Principle studies the growth rate of minimal surfaces. All we need is the simple consequence of the Monotonicity Principle, Proposition 3.1, stated below. For illustration purposes, we give two proofs of Proposition 3.1 in the special case when the minimal surface intersects the ball in a (topological) disk. We will use the following facts about minimal surfaces: (1) if a minimal surface F intersects a small totally geodesic disk D and locally F is contained on one side of D then $D \subseteq F$. (2) If D is a little piece of the round sphere ∂B (for some metric ball B) and $F \cap D \neq \emptyset$, then locally $D \not\subset F$. Roughly speaking, these facts state that a minimal surface cannot have "maxima" (or, the maximum principle for minimal surfaces).

In this section we use the following notation: $B(r)$ is a hyperbolic ball of radius r, its center is O and its boundary $\partial B(r)$. A great circle is a circle in $\partial B(r)$ given by the intersection of $B(r)$ with a totally geodesic disk centered at O. For convenience we use the Poincaré ball model, use the horizontal circle (*i.e.*, the equator) as a great circle and denote the totally geodesic disk it bounds D_0. ∂D_0 separates $\partial B(r)$ into the northern and southern hemispheres, and D_0 separates $B(r)$ into the northern and southern half balls. The ball is foliated by geodesic disks D_t ($-r \leq t \leq +r$), where D_t is the intersection of $B(r)$ with the geodesic plane that is perpendicular to the z-axis and intersects it at $(0, 0, t)$. Here and throughout this paper, we denote the area of a hyperbolic disk of radius r by $a(r)$. In the first proof below we use the fact that if a curve on a sphere intersects every great circle then it is at least as long as a great circle (Proposition A.1). This is an elementary fact in spherical geometry. In Appendices A and B we give two proofs of this fact, however, we encourage the reader to find her/his own proof and send it to us.

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Proposition 3.1. *Let $B(R)$ be a hyperbolic ball of radius R centered at O and $F \subset M$ a minimal surface so that $O \in F$. Then the area of F is at least $a(R)$.*

We refer the reader to [18] for a proof. For the remainder of the section, assume $F \cap B(R)$ is topologically a disk. Then we have:

First proof. Fix r, $0 < r \leq R$. Let C be a great circle in $\partial B(r)$ (which for convenience we call the equator). We claim that either $F \cap \partial B(r)$ is the equator or $F \cap \partial B(r)$ intersects both the northern and southern hemispheres.

Suppose for contradiction for some r this is not the case. Then one of the following holds:

(1) $F \cap \partial B(r) = \emptyset$.
(2) $F \cap \partial B(r)$ does not intersect one of the two hemispheres.

Assuming Case (1) happens, and let $t > 0$ be the largest value for which $F \cap \partial B(t) \neq \emptyset$. Then F and $\partial B(t)$ contradict fact (2) mentioned above.

Next assume Case (2) happens (say F does not intersect the southern hemisphere). Let t be the most negative value for which $F \cap D_t \neq \emptyset$. Since $O \in F$, $-r < t \leq 0$. Then by fact (1) above, F must coincide with D_t. If $t < 0$ then D_t intersects the southern hemisphere, contrary to our assumptions. Hence $t = 0$ and F is itself D_0; thus $F \cap B(r)$ is the equator, again contradicting our assumptions.

By assumption $F \cap B(R)$ is a disk and therefore $F \cap \partial B(r)$ is a circle. Clearly, a circle that intersects both the northern and the southern hemispheres must intersect the equator. We conclude that $F \cap \partial B(r)$ intersects the equator, and as the equator was chosen arbitrarily, $F \cap \partial B(r)$ intersects every great circle. By Proposition A.1 $l(F \cap B(r))$ is at least the length of a great circle in $\partial B(r)$. Integrating these lengths shows that the area of $F \cap B(r)$ grows at least as fast as the area of a geodesic disk, proving the proposition. □

Second proof. Restricting the metric from M to F, distances can increase but cannot decrease. Therefore $F \cap \partial B(R)$ is at distance (on F) at least R from O and we conclude that F contains an entire disk of radius R. The induced metric on F has curvature ≤ -1 and therefore areas on F are $\geq$ areas in $\mathbb{H}^3$. In particular, the disk of radius R about O has area $\geq a(R)$. □

4. MAIN THEOREM

By Section 2 the main task in proving Theorem 1.1 is homotoping minimal surfaces of genus $\leq h$ into fibers. We generalize the necessary result here:

Theorem 4.1. *Let M be a hyperbolic manifold and $F \subset M$ a non-separating surface. Let M_d denote the cyclic cover of M dual to F of degree d (as in the introduction).*

Then for any integer $h \geq 0$ there exists a constant n so that for $d \geq n$, any minimal surface of genus $\leq h$ in M_d can be isotoped to be disjoint from a component of the preimage of F.

Proof. Fix an integer h.

Denote the distance in M by $d(\cdot,\cdot)$. Push F slightly to obtain $\widehat{F}$, a surface parallel to F and disjoint from it. For each point $p \in F$ define:

$$R(p) = \min\{\text{radius of injectivity at } p,\ d(p,\widehat{F})\}.$$

Since $\widehat{F}$ is compact $R(p) > 0$. Define:

$$R = \min\{R(p) | p \in F\}.$$

Since F is compact $R > 0$. Note that R has the following property: for any $p \in F$, the set $\{q \in M : d(p,q) < R\}$ is an embedded ball and this ball is disjoint from $\widehat{F}$. Let $a(R)$ denote the area of a hyperbolic disk of radius R.

Let n be the smallest integer bigger than $\frac{2\pi(2h-2)}{a(R)}$. Fix an integer $d \geq n$. Denote the preimages of F in M_d by $F_1, \dots, F_d$.

Let S be a minimal surface in M_d. Suppose S cannot be isotoped to be disjoint from the preimages of F_i for any i. We will show that $g(S) > h$, proving the theorem.

Pick a point $p_i \in F_i \cap S$ ($i = 1, \dots, d$) and let B_i be the set $\{p \in M_d | d(p, p_i) < R\}$. By choice of R, for each i, B_i is an embedded ball and the preimages of $\widehat{F}$ separate these balls. $S \cap B_i$ is a minimal surface in B_i that intersects its center and by Proposition 3.1 (the Monotonicity Principle) has area at least $a(R)$. Summing these areas we see that the area of S fulfills:

$$\begin{aligned} \text{Area of } S &\geq d \cdot a(R) \\ &\geq n \cdot a(R) \\ &> \frac{2\pi(2h-2)}{a(R)} \cdot a(R) \\ &= 2\pi(2h-2). \end{aligned}$$

But a minimal surface in a hyperbolic manifold has curvature ≤ -1 and hence by the Gauss-Bonnet Theorem, the area of $S \leq -2\pi\chi(S) = 2\pi(2g(S-2)$. Hence, the genus of S is greater than h. □

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Remark 4.2 (Suggested project). In Theorem 4.1 we treat the covers dual to a non-separating essential surface (denoted M_d there). In the section titled "Generalization" of [9], Lackenby shows (among other things) how to amalgamate along non-separating surfaces. Does his construction and Theorem 4.1 give useful bounds on the genus of M_d, analogous to Theorem 1.1?

5. LACKENBY'S THEOREM

Lackenby studied the Heegaard genus of manifolds containing separating essential surfaces. Here too, the result is asymptotic. We begin by explaining the set up. Let N_1 and N_2 be hyperbolic manifolds with $\partial N_1 \cong \partial N_2$ a connected surface of genus $g \geq 2$. Let S be a surface of genus g and $\psi_i : S \to \partial N_i$ parameterizations of the boundaries ($i = 1, 2$). Let $f : S \to S$ be a pseudo-Anosov map. For any n we construct the map $f_n = \psi_2 \circ f^n \circ (\psi_1)^{-1} : \partial N_1 \to \partial N_2$. By identifying ∂N_1 with ∂N_2 by the map f_n we obtain a closed hyperbolic manifold M_n. Let $S \subset M_n$ be the trace of $\partial N_1 = \partial N_2$. With this we are ready to state Lackenby's Theorem:

Theorem 5.1 (Lackenby [9]). *With notation as in the previous paragraph, for any h there exists N so that for any $n \geq N$ any genus h Heegaard surface for M_n weakly reduces to S. In particular, by setting $h = g(N_1) + g(N_2) - g(S)$ we see that there exists N so that if $n \geq N$ then $g(M_n) = g(N_1) + g(N_2) - g(S)$.*

Sketch of proof. As in Sections 2 and 4, the proof has two parts which we bring here as two claims:

Claim 1. *Suppose that every every minimal surface in M_n of genus $\leq h$ can be homotoped to be disjoint from S. Then any Heegaard surface of genus $\leq h$ weakly reduces to S. In particular, if $h \geq g(N_1) + g(N_2) - g(S)$ then $g(M_n) = g(N_1) + g(N_2) - g(S)$.*

Claim 2. *There exists N so that if $n \geq N$ then any minimal surface of genus $\leq h$ in M_n can be homotoped to be disjoint from S.*

Clearly, Claim 1 and 2 imply Lackenby's Theorem. We now sketch their proofs.

We paraphrase Lackenby's proof of Claim 1: let Σ be a Heegaard surface of genus $\leq h$. Then by Scharlemann and Thompson [15] Σ untelescopes to a collection of connected surfaces F_i and Σ_j where $\cup_i F_i$ is an essential surface (with F_i its components) and Σ_j are strongly irreducible Heegaard surfaces for the components of M_n cut open along $\cup_i F_i$; in particular M cut open along $(\cup_i F_i) \cup (\cup_i \Sigma_j)$ consists of compression bodies and the traces of the Σ_j's form ∂_- of these compression bodies. Since F_i and Σ_j are obtained by compressing Σ, they all have genus $\leq h$. By [16], [2], and [11] the surfaces F_i and Σ_j can be made minimal. By assumption, S can be isotoped to be disjoint from them. Therefore, S is an essential surface in a compression body and is parallel to a component of ∂_-. Therefore, for some i, S is isotopic to F_i. In [8] it was shown that if Σ untelescopes to the added
essential surface $\cup_i F_i$, then Σ weakly reduces to any *connected separating* component of $\cup_i F_i$; therefore Σ weakly reduces to S. This proves the first part of Claim 1.

Since S is connected any minimal genus Heegaard splittings for N_1 and N_2 can be amalgamated (the converse of weak reduction [17]). By amalgamating minimal genus Heegaard surfaces we see that for any n, $g(M_n) \leq$

$g(N_1) + g(N_2) - g(S)$. By applying the first part of Claim 1 to $h = g(N_1)+g(N_2)-g(S)$ we see that for sufficiently large n, $g(M_n) \geq g(N_1)+g(N_2) - g(S)$ as well, completing the proof of Claim 1.

We now sketch the proof of Claim 2. Fix h and assume that for arbitrarily high values of n, M_n contains a minimal surface (say P_n) of genus $g(P_n) \leq h$ that cannot be homotoped to be disjoint from S. Let M_f be the bundle over S^1 with monodromy f and fix two disjoint fibers F, $\widehat{F} \subset M_f$. Let R be as in Section 4. Let M_∞ be the infinite cyclic cover dual to the fiber. Soma [19] showed that there are points $x_n \in M_n$ so that (M_n, x_n) converges in the sense of Hausdorff–Gromov to the manifold M_∞. These points are near the minimal surface S, and the picture is that M_n has a very long "neck" that looks more and more like M_∞.

For sufficiently large n there is a ball $B(r) \subset M_n$ for arbitrarily large r that is $1-\epsilon$ isometric to $B_\infty(r) \subset M_\infty$. Note that $B_\infty(r)$ contains arbitrarily many lifts of F separated by lifts of $\widehat{F}$. Since P_n cannot be isotope d to be disjoint from S, it image in M_∞ cannot be isotoped off the preimages of F. As in Section 4 we conclude that the images of P_n have arbitrarily high area. However, areas cannot be distorted arbitrarily by a map that is $1 - \epsilon$ close to an isometry. Hence the area of P_n are unbounded, contradicting Gauss–Bonnet; this contradiction completes our sketch. □

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In [20] Souto generalized Lackenby's result. Although his work does not involve bundles over S^1 and is beyond the scope of this paper, we give a brief description of it here. Instead of powers of maps, Souto used a combinatorial condition on the gluings: fixing essential curves $\alpha_i \subset N_i$ ($i = 1, 2$) and $h > 0$, Souto shows that if $\phi : N_1 \to N_2$ fulfills the condition "$d_{\mathcal{C}}(\phi(\alpha_1), \alpha_2)$ is sufficiently large" then any Heegaard splitting for $N_1 \cup_\phi N_2$ of genus $\leq h$ weakly reduces to S. The distance Souto uses—$d_{\mathcal{C}}$—is the distance in the "curve complex" and *not* the hyperbolic distance. We will not describe this distance here, but we do mention that Hempel [5] (following Kobayashi [7]) showed that raising a fixed monodromy ϕ to a sufficiently high power does imply Souto's condition. Hence Souto's condition is indeed weaker than Lackenby's, and it is in fact too weak for us to expect Soma-type convergence to M_∞. However, using Minsky [10] Souto shows that given a sequence of manifolds M_{ϕ_n} with $d_{\mathcal{C}}(\phi_n(\alpha_1), \alpha_2) \to \infty$, the manifolds M_{ϕ_n} are "torn apart" and the cores of N_1 and N_2 become arbitrarily far apart. For a precise statement see Proposition 6 of [20]. Souto concludes that for sufficiently large n, any minimal surface for M_n that intersects both N_1 and N_2 has high area and therefore genus greater than h. Souto's Theorem now follows from Claim 1 above.

APPENDIX A. SHORT CURVES ON ROUND SPHERES: TAKE ONE

In this section we prove the following proposition, which is a simple exercise in spherical geometry used in Section 3. Let $S^2(r)$ be a sphere of constant curvature $+(\frac{1}{r})^2$. We isometrically identify $S^2(r)$ with $\{(x,y,z) \in \mathbb{R}^3 | x^2+y^2+z^2=r^2\}$ and refer to it as a round sphere of radius r.

Proposition A.1. *Let $S^2(r)$ be a round sphere of radius r and $\gamma \subset S^2$ a rectifiable closed curve. Suppose $l(\gamma) \leq 2\pi r$ (the length of great circles). Then γ is disjoint from some great circle.*

Remark. The proof also shows that if γ is a *smooth* curve the meets every great circle then $l(\gamma) = 2\pi r$ if and only if γ is itself a great circle.

Proof. Let γ be a curve that intersects every great circle. Let z_{min} (for some $z_{\text{min}} \in \mathbb{R}$) be the minimal value of the z-coordinate, taken over γ. Rotate $S^2(r)$ to maximize z_{min}. If $z_{\text{min}} > 0$ then γ is disjoint from the equator, contradicting our assumption. We assume from now on $z_{\text{min}} \leq 0$.

Suppose first $z_{\text{min}} = 0$. Suppose, for contradiction, that there exists a closed arc α on the equator so that $l(\alpha) = \pi r$ and $\alpha \cap \gamma = \emptyset$. By rotating $S^2(r)$ about the z-axis (if necessary) we may assume $\alpha = \{(x,y,0) \in S^2(r) | y \leq 0\}$. Then rotating $S^2(r)$ slightly about the x-axis pushes the points $\{(x,y,0) \in S^2(r) | y > 0\}$ above the xy-plane. By compactness of γ and α there is some ϵ so that $d(\gamma,\alpha) > \epsilon$. Hence if the rotation is small enough, no point of γ is moved to (or below) α. Thus, after rotating $S^2(r)$, $z_{\text{min}} > 0$, contradiction. We conclude that every arc of the equator of length πr contains a point of γ. Therefore there exists a sequence of point $p_i \in \gamma \cap \{(x,y,0)\}$ ($i = 1,\dots,n$, for some $n \geq 2$), ordered by their order along the equator (*not* along γ), so that $d(p_i,p_{i+1})$ is at most half the equator (indices taken modulo n). The shortest path connecting p_i to p_{i+1} is an arc of the equator, and we conclude that $l(\gamma) \geq 2\pi r$ as required. If we assume, in addition, that $l(\gamma) = 2\pi r$ then either γ is itself the equator or γ consists of two arcs of great circle meeting at $c_1 \cup c_2$. Note that this can in fact happen, but then γ is not smooth. This completes the proof in the case $z_{\text{min}} = 0$

Assume next $z_{\text{min}} < 0$. Let c_{min} be the latitude of $S^2(r)$ at $z = z_{\text{min}}$, and denote the length of c_{min} by d_{min}. Suppose there is an open arc of c_{min} of length $\frac{1}{2}d_{\text{min}}$ that does not intersect γ. Similar to above, by rotating $S^2(r)$ we may assume this arc is given by $\{(x,y,z_{\text{min}}) \in c_{\text{min}} | y < 0\}$. Then a tiny rotation about the x-axis increases the z-coordinate of all points $\{(x,y,z) | y \geq 0,\ z \leq 0\}$. As above ,this increases z_{min}, contradicting our choice of z_{min}. Therefore there is a collection of points $p_i \in \gamma \cap c_{\text{min}}$ ($i = 1,\dots,n$, for some $n \geq 3$), ordered by their order along the equator (*not* along c_{min}), so that $d(p_i,p_{i+1}) < \frac{1}{2}d_{\text{min}}$ (indices taken modulo n).

The shortest path connecting p_i to p_{i+1} is an arc of a great circle. However, such arc has points with z-coordinate less than z_{min}, and therefore cannot be a part of γ. The shortest path containing all the p_i's on the punctured sphere on $\{(x, y, z) \in S^2(r) | z \geq z_{\text{min}}\}$ is the boundary, that is, c_{min} itself. Unfortunately, $l(c_{\text{min}}) < 2\pi r$. Upper hemisphere to the rescue! γ must have a point with z-coordinate at least $-z_{\text{min}}$, for otherwise rotating $S^2(r)$ by π about any horizontal axis would decrease z_{min}. Then $l(\gamma)$ is at least as long as the shortest curve containing the p_i's and some point p on or above c_{min}, the circle of γ at $z = z_{\text{min}}$. Let γ be such a curve. By reordering the indices if necessary it is convenient to assume that p is between p_1 and p_2. It is clear that moving p so that its longitude is between the longitudes of p_1 and p_2 shortens γ (note that since $d(p_1, p_2) < \frac{1}{2} d_{\text{min}}$ this is well-defined). We now see that γ intersects the equator in two point, say x_1 and x_2. Replacing the two arcs of γ above the equator by the short arc of the equator decreases length. It is not hard to see that the same hold when we replace the arc of γ below the equator with the long arc of the equator. We conclude that $l(\gamma) \geq l(\gamma) > 2\pi r$. □

APPENDIX B. SHORT CURVES ON ROUND SPHERES: TAKE TWO

We now give a second proof of Proposition A.1. For convenience of presentation we take S^2 to be a sphere of radius 1. Let γ be a closed curve that intersects every great circle. Every great circle is defined by two antipodal points, for example, the equator is defined by the poles. Thus, the space of great circles is $\mathbb{R}P^2$. Since S^2 has area 4π, $\mathbb{R}P^2$ has area 2π. Let $f : S^2 \to \mathbb{R}P^2$ be the "map" that assigns to a point p all the great circles that contain p; thus, for example, if p is the north pole then $f(p)$ is the projection of the equator to $\mathbb{R}P^2$.

Let C be a great circle. We claim that $\gamma \cap C$ contains at least two points of γ. (If γ is not embedded then the two may be the same point of C.) Suppose, for a contradiction, that γ meets some great circle (say the equator) in one point only (Say $(1, 0, 0)$). By the Jordan Curve Theorem, γ does not cross the equator. By tilting the equator slightly about the y-axis it is easy to obtain a great circle disjoint from γ. Hence we see that γ intersects every great circle at least twice. Equivalently, $f(\gamma)$ covers $\mathbb{R}P^2$ at least twice.

Let α_i be a small arc of a great circle, of length $l(\alpha_i)$; note that this length is exactly the angle α_i supports in radians. Say for convenience α_i starts at the north pole and goes towards the equator. The points that define great circles that intersect α_i are given by tilting the equator by α_i radians. This gives a set whose area is α_i/π of the total area of S^2. Since the area of S^2 is 4π, it gives a set of area $4l(\alpha_i)$. This set is invariant under the antipodal map, and so projecting to $\mathbb{R}P^2$ the area is cut by half, and we get:

(1) $$\text{Area of } f(\alpha_i) = 2l(\alpha_i).$$

Fix $\epsilon > 0$. Let α be an approximation of γ by small arcs of great circles, say $\{\alpha_i\}_{i=1}^n$ are the segments of α. We require α to approximate γ well in the following two senses:

(1) $l(\alpha) \leq l(\gamma) + \epsilon$.
(2) Under f, α covers $\mathbb{R}P^2$ as well as γ does (except, perhaps, for a set of measure ϵ); *i.e.*, the area of $f(\alpha) \geq$ the area of $f(\gamma) - \epsilon$ (area measured with multiplicity). ??

From this we get:

$$\begin{aligned} 4\pi - \epsilon &= \text{twice the area of } \mathbb{R}P^2 - \epsilon \\ &\leq \text{the area of } f(\gamma) - \epsilon \\ &\leq \text{area of } f(\alpha) \\ &= \Sigma_{i=1}^n \text{area of } f(\alpha_i) \\ &= \Sigma_{i=1}^n 2l(\alpha_i) \\ &= 2l(\alpha) \\ &\leq 2(l(\gamma) + \epsilon). \end{aligned}$$

(In the fifth equality we use Equation (1).) Since ϵ was arbitrary, dividing by 2 we get the desired result: $2\pi \leq l(\gamma)$.

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