

# MANIFOLDS WITH QUADRATIC CURVATURE DECAY AND SLOW VOLUME GROWTH

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*To Detlef Gromoll on his 60th birthday*

ABSTRACT. – We show that there are topological obstructions for a noncompact manifold to admit a Riemannian metric with quadratic curvature decay and a volume growth which is slower than that of the Euclidean space of the same dimension. © 2000 Éditions scientifiques et médicales Elsevier SAS

RÉSUMÉ. – Nous montrons qu'il y a des obstructions topologiques pour qu'une variété non compacte admette une métrique Riemannienne à courbure quadratiquement décroissante ainsi qu'une croissance de volume plus lente que celle de l'espace Euclidien de même dimension. © 2000 Éditions scientifiques et médicales Elsevier SAS

## 1. Introduction

A major theme in Riemannian geometry is the relationship between curvature and topology. For compact manifolds, one can constrain the curvature and diameter and ask whether one obtains topological restrictions on the manifold. If the manifold is noncompact then a replacement for a diameter bound is a constraint on how the curvature behaves in terms of the distance from a basepoint. More precisely, let  $M$  be a complete connected  $n$ -dimensional Riemannian manifold. Fix a basepoint  $m_0 \in M$ .

DEFINITION 1.1. –  $M$  has quadratic curvature decay (with constant  $C > 0$ ) if for all  $m \in M$  and all 2-planes  $P$  in  $T_m M$ , the sectional curvature  $K(P)$  of  $P$  satisfies

$$(1) \quad |K(P)| \leq C/d(m_0, m)^2.$$

Note that condition (1) is scale-invariant in that it is unchanged by a constant rescaling of the Riemannian metric. One can show that any connected smooth paracompact manifold has a Riemannian metric with quadratic curvature decay; see [10, p. 96] or Lemma 2.1 below. Let us contrast this with the result of Abresch [1] that if  $K(P) \geq -C/d(m_0, m)^{2+\varepsilon}$  for some  $\varepsilon > 0$  then  $M$  has finite topological type in the following sense.

DEFINITION 1.2. –  $M$  has finite topological type if  $M$  is homotopy-equivalent to a finite CW-complex.

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See [1,9] for results on manifolds with faster-than-quadratic curvature decay. In this paper we concentrate instead on the case of quadratic curvature decay. We will show that if in addition one restricts the volume growth of the metric, then one does obtain topological restrictions on  $M$ . The first question is whether  $M$  has finite topological type.

DEFINITION 1.3. –  $M$  has lower quadratic curvature decay (with constant  $C > 0$ ) if for all  $m \in M$  and all 2-planes  $P$  in  $T_m M$ , the sectional curvature  $K(P)$  of  $P$  satisfies

$$(2) \quad K(P) \geq -C/d(m_0, m)^2.$$

Let  $B_t$  denote the metric ball of radius  $t$  around  $m_0$  and let  $S_t$  denote the distance sphere of radius  $t$  around  $m_0$ . If  $M$  has lower quadratic curvature decay then by a standard argument,  $M$  has at most polynomial volume growth; see [7, Theorem 4.9(iii)] or Lemma 3.1 below.

PROPOSITION 1.1. – *Suppose that  $M$  has lower quadratic curvature decay. If  $\text{vol}(B_t) = o(t^2)$  as  $t \rightarrow \infty$  and  $M$  does not collapse at infinity, i.e.  $\inf_{x \in M} \text{vol}(B_1(x)) > 0$ , then  $M$  has finite topological type.*

The  $o(t^2)$  bound in Proposition 1.1 cannot be improved to  $O(t^2)$ , as shown in Example 3 below. Proposition 1.1 is an improvement of [11, Theorem 1.2], where an additional assumption of nonnegative Ricci curvature was made.

Next, we consider manifolds with volume growth slower than that of the Euclidean space of the same dimension.

DEFINITION 1.4. –  $M$  has slow volume growth if

$$(3) \quad \liminf_{t \rightarrow \infty} \text{vol}(B_t)/t^n = 0.$$

There is a notion of an end  $E$  of  $M$  and of  $E$  being contained in an open set  $\mathcal{O} \subset M$ ; see, for example, [2, p. 80].

DEFINITION 1.5. – An end  $E$  of  $M$  is tame if it is contained in an open set diffeomorphic to  $(0, \infty) \times X$  for some smooth connected closed manifold  $X$ .

We remark that  $X$  is determined by  $E$  only up to  $h$ -cobordism. Hereafter we assume that  $M$  is oriented.

PROPOSITION 1.2. – *Suppose that  $M$  has quadratic curvature decay and slow volume growth. Let  $E$  be a tame end of  $M$  as in Definition 1.5. Then for any product  $\prod_k p_{i_k}(TX)$  of Pontryagin classes of  $X$  and any bounded cohomology class  $\omega \in H^l(X; \mathbb{R})$  with  $l + 4 \sum_k i_k = n - 1$ ,*

$$(4) \quad \int_X \omega \cup \prod_k p_{i_k}(TX) = 0.$$

COROLLARY 1.1. – *If  $M$  is as in Proposition 1.2 then the signature and the simplicial volume of  $X$  vanish.*

Example. – There is no metric of quadratic curvature decay and slow volume growth on  $\mathbb{R} \times \mathbb{C}P^{2k}$ .

Next, we give a sufficient condition for  $M$  to have a metric of quadratic curvature decay and slow volume growth.

PROPOSITION 1.3. – *Let  $X$  be a closed manifold with a polarized  $F$ -structure [5]. Suppose that  $X = \partial N$  for some smooth compact manifold  $N$ . Then there is a complete Riemannian metric on  $M = \text{Int}(N)$  of quadratic curvature decay and slow volume growth.*

It follows from Proposition 1.3 that when  $n$  is even, there is a metric on  $\mathbb{R}^n$  of quadratic curvature decay and slow volume growth. The case when  $n$  is odd is less obvious.

PROPOSITION 1.4. – *For all  $n > 1$ , there is a complete Riemannian metric on  $\mathbb{R}^n$  of quadratic curvature decay and slow volume growth.*

If  $X$  is a closed oriented manifold with a polarized  $F$ -structure then the Pontryagin numbers and Euler characteristic of  $X$  vanish. Based on Proposition 1.3, one may think that under the hypotheses of Proposition 1.2, one could also show that the Euler characteristic of  $X$  vanishes. However, Proposition 1.4 shows that this is not the case, as the Euler characteristic of  $S^{n-1}$  is two if  $n$  is odd.

We can combine Propositions 1.2–1.4 to obtain some low-dimensional results.

COROLLARY 1.2. – *Let  $N$  be a smooth compact connected oriented manifold-with-boundary of dimension  $n$ .*

- (1) *If  $n = 2$  then  $\text{Int}(N)$  has a metric of quadratic curvature decay and slow volume growth.*
- (2) *If  $n = 3$  then  $\text{Int}(N)$  has a metric of quadratic curvature decay and slow volume growth if and only if  $\partial N$  consists of 2-spheres and 2-tori.*
- (3) *If  $n = 4$ , suppose that Thurston’s Geometrization Conjecture holds. Then  $\text{Int}(N)$  has a metric of quadratic curvature decay and slow volume growth if and only if the connected components of  $\partial N$  are graph manifolds.*

Finally, by an argument similar to that of [6, Theorem 0.8], there is an integrality result for the integral of the Gauss–Bonnet–Chern form, which we state without proof.

PROPOSITION 1.5. – *Suppose that  $M$  has a complete Riemannian metric  $g$  of quadratic curvature decay with*

$$\text{vol}(B_t) = o(t^n) \quad \text{and} \quad \int_1^\infty \frac{\text{vol}(B_t)}{t^n} \frac{dt}{t} < \infty.$$

*Let  $e(M, g) \in \Omega^n(M)$  be the Gauss–Bonnet–Chern form. Then  $\int_M e(M, g) \in \mathbb{Z}$ .*

As mentioned above, any connected smooth paracompact manifold admits a Riemannian metric with quadratic curvature decay. An interesting question, which makes no reference to volume growth, is how small the constant  $C$  in Definition 1.1 can be made. That is, given  $C > 0$ , what are the topological constraints on the noncompact manifolds which admit complete Riemannian metrics satisfying  $|K(P)| \leq C/(1 + d(m_0, m))^2$ ?

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## 2. Examples

(1) Let  $N$  be a smooth compact connected  $n$ -dimensional manifold-with-boundary. Let  $h$  be a metric on  $\partial N$ . Given  $c \geq 1$ , consider the metric on  $[1, \infty) \times \partial N$  given by  $dt^2 + t^{2c}h$ . Extend this to a smooth metric  $g$  on  $\text{Int}(N) = N \cup_{\partial N} ([1, \infty) \times \partial N)$ . Then  $g$  has quadratic curvature decay and polynomial volume growth. By choosing  $c$  large, the degree of volume growth can be made

arbitrarily large. Taking  $c = 1$ , we see that having quadratic curvature decay and volume growth of order  $O(t^n)$  in no way restricts the topology of the ends.

(2) For  $c \in \mathbb{R}$ , consider the metric on  $[1, \infty) \times S^1$  given by  $dt^2 + t^{2c} d\theta^2$ . Cap this off by a disk at  $\{1\} \times S^1$  to obtain a smooth metric  $g$  on  $\mathbb{R}^2$ . Then  $g$  has quadratic curvature decay. If  $c < -1$  then  $(\mathbb{R}^2, g)$  has finite volume. Hence the assumption of quadratic curvature decay gives no nontrivial lower bound on volume growth.

(3) Start with the Euclidean metric on the annulus

$$(5) \quad A = \{(x, y) \in \mathbb{R}^2: 1 \leq x^2 + y^2 \leq 4\} = \overline{B_2(0)} - B_1(0).$$

Add a handle to  $\text{Int}(A)$ , keeping the metric the same near  $\partial A$ . Consider this as a metric on  $T^2 - D^2 - D^2$ . With an obvious notation, for  $j \in \mathbb{N}$ , let  $2^j \cdot (T^2 - D^2 - D^2)$  denote the rescaled metric. Consider the infinite genus surface

$$(6) \quad \Sigma = \overline{B_1(0)} \cup_{S^1} (T^2 - D^2 - D^2) \cup_{S^1} 2 \cdot (T^2 - D^2 - D^2) \cup_{S^1} 4 \cdot (T^2 - D^2 - D^2) \cup_{S^1} \dots$$

with its corresponding metric  $g_\Sigma$ . For  $n \geq 2$ , let  $g_{T^{n-2}}$  be a flat metric on the  $(n - 2)$ -torus. Then the product metric  $(\Sigma, g_\Sigma) \times (T^{n-2}, g_{T^{n-2}})$  has quadratic curvature decay, volume growth of order  $t^2$  and infinite topological type. This shows that the  $o(t^2)$  condition in Proposition 1.1 cannot be improved to  $O(t^2)$ .

LEMMA 2.1. – *If  $M$  is a smooth connected paracompact manifold then  $M$  admits a complete Riemannian metric of quadratic curvature decay.*

*Proof.* – First,  $M$  admits a complete Riemannian metric  $h$  of bounded sectional curvature [8]. Given  $\phi \in C^\infty(M)$ , put  $g = e^{2\phi}h$ . We have

$$(7) \quad R_{jkl}^i(g) = R_{jkl}^i(h) - \tilde{\phi}_k^i h_{jl} + \tilde{\phi}_l^i h_{jk} - \delta_k^i \tilde{\phi}_{jl} + \delta_l^i \tilde{\phi}_{jk} - \phi_{;r} \phi^{;r} (\delta_k^i h_{jl} - \delta_l^i h_{jk}),$$

where  $\tilde{\phi}_{ab} = \phi_{;ab} - \phi_{;a} \phi_{;b}$ . Let  $d_h$  denote the distance function with respect to  $h$  and let  $d_g$  denote the distance function with respect to  $g$ . By [6, Theorem 1.8], there is a  $\phi \in C^\infty(M)$  and a constant  $c > 0$  such that

- (1)  $\phi(m) \leq d_h(m_0, m) \leq \phi(m) + c$ .
- (2)  $\|\nabla \phi\|_\infty \leq c$ .
- (3)  $\|\text{Hess}(\phi)\|_\infty \leq c$ .

Then from (7), in order to show that  $g$  has quadratic curvature decay it suffices to show that there is a constant  $C > 0$  such that  $d_g(m_0, m) \leq C e^{\phi(m)}$  for all  $m \in M$ . Let  $\gamma$  be a normalized minimal geodesic, with respect to  $h$ , from  $m_0$  to  $m$ . Then measuring the length of  $\gamma$  with respect to  $g$ ,

$$(8) \quad d_g(m_0, m) \leq \int_0^{d_h(m_0, m)} e^{\phi(\gamma(t))} dt \leq \int_0^{d_h(m_0, m)} e^t dt = e^{d_h(m_0, m)} - 1 \leq e^c e^{\phi(m)}.$$

The lemma follows.  $\square$

### 3. Proof of Proposition 1.1

First of all, every manifold with lower quadratic Ricci curvature decay has polynomial volume growth [7, Theorem 4.9(iii)]. For completeness, and as we will need Eq. (11) below, we give the proof here.

LEMMA 3.1. – *Suppose that there is a constant  $C > 0$  such that for each  $m \in M$  and each unit vector  $v \in T_m M$ , the Ricci curvature satisfies*

$$(9) \quad \text{Ric}(v, v) \geq -(n - 1) \frac{C}{d(m_0, m)^2}.$$

Put  $N = (n - 1)((\sqrt{1 + 4C} - 1)/2) + n$ . Then there is a constant  $C_0 = C_0(n, C) > 0$  such that for  $t \geq 3$ ,

$$(10) \quad \text{vol}(B_t) \leq C_0 \text{vol}(S_1)t^N + \text{vol}(B_1)$$

and

$$(11) \quad \text{vol}(B_{t+1} - B_{t-1}) \leq C_0 \frac{\text{vol}(B_{t-1})}{t - 1}.$$

*Proof.* – Let  $\Pi_t = \frac{1}{n-1} \sum_{i=1}^{n-1} k_i$  denote the mean curvature of the regular part of  $S_t$ , where  $\{k_i\}_{i=1}^{n-1}$  are the principal curvatures. Letting  $dA_t$  and  $dA_{m_0}$  denote the volume forms on  $S_t$  and  $S_{m_0}M$  respectively, define  $\varphi_t: S_{m_0}M \rightarrow S_t$  by

$$(12) \quad \varphi_t(v) = \exp_{m_0}(tv)$$

and define  $\eta_t: S_{m_0}M \rightarrow (0, \infty)$  by

$$(13) \quad (\varphi_t)^* dA_t|_v = \eta_t(v) dA_{m_0}.$$

We have

$$(14) \quad \text{vol}(S_t) = \int_{S_{m_0}M} \eta_t(v) dA_{m_0}$$

and

$$(15) \quad (n - 1)\Pi_t|_{\varphi_t(v)} = \eta'_t(v)/\eta_t(v).$$

As  $t \rightarrow 0$ ,

$$(16) \quad (n - 1)\Pi_t|_{\varphi_t(v)} = \frac{n - 1}{t} - \frac{\text{Ric}(v, v)}{3}t + o(t).$$

Put  $\Pi(t) = \Pi_t|_{\varphi_t(v)}$  and  $v(t) = (\exp_{m_0})_*(tv)$ . The Riccati equation implies

$$(17) \quad \Pi'(t) + \Pi(t)^2 \leq -\frac{\text{Ric}(v(t), v(t))}{n - 1}.$$

Put  $\alpha = (\sqrt{1 + 4C} + 1)/2$  and consider

$$(18) \quad f(t) = e^{\int_1^t \Pi(s) ds} [t^\alpha \Pi(t) - \alpha t^{\alpha-1}].$$

Then (16) implies that  $\lim_{t \rightarrow 0^+} f(t) = 0$ . On the other hand, from (9) and (17), we have

$$(19) \quad f'(t) = t^\alpha e^{\int_1^t \Pi(s) ds} [\Pi'(t) + \Pi(t)^2 - \alpha(\alpha - 1)t^{-2}] \leq 0.$$

Thus  $f(t) \leq 0$ , giving

$$(20) \quad \Pi(t) \leq \alpha t^{-1}.$$

Together with (15), we conclude that  $\eta_t(v)/t^{(n-1)\alpha}$  is nonincreasing. This implies that  $\text{vol}(S_t)/t^{(n-1)\alpha}$  is nonincreasing, too. As

$$(21) \quad \text{vol}(B_t) - \text{vol}(B_1) = \int_1^t \frac{\text{vol}(S_s)}{s^{(n-1)\alpha}} s^{(n-1)\alpha} ds,$$

we obtain

$$(22) \quad \text{vol}(S_1) \int_1^t s^{(n-1)\alpha} ds \geq \text{vol}(B_t) - \text{vol}(B_1) \geq \frac{\text{vol}(S_t)}{t^{(n-1)\alpha}} \int_1^t s^{(n-1)\alpha} ds.$$

Hence

$$(23) \quad \text{vol}(B_t) \leq \frac{1}{(n-1)\alpha + 1} \text{vol}(S_1) t^{(n-1)\alpha + 1} + \text{vol}(B_1).$$

Also,

$$(24) \quad \begin{aligned} \text{vol}(B_{t+1} - B_{t-1}) &= \int_{t-1}^{t+1} \frac{\text{vol}(S_s)}{s^{(n-1)\alpha}} s^{(n-1)\alpha} ds \leq \frac{\text{vol}(S_{t-1})}{(t-1)^{(n-1)\alpha}} \int_{t-1}^{t+1} s^{(n-1)\alpha} ds \\ &\leq \frac{\text{vol}(B_{t-1}) - \text{vol}(B_1)}{\int_1^{t-1} s^{(n-1)\alpha} ds} \int_{t-1}^{t+1} s^{(n-1)\alpha} ds \\ &\leq C_0 \frac{\text{vol}(B_{t-1})}{t-1} \end{aligned}$$

for large enough  $C_0$ .  $\square$

*Proof of Proposition 1.1.* – We use critical point theory of the distance function; for a review, see [3]. Let us say that a connected component  $\Sigma_t$  of  $S_t$  is *good* if it is part of the boundary of an unbounded component of  $M - \overline{B}_t$  and there is a ray from  $m_0$  passing through  $\Sigma_t$ .

LEMMA 3.2. – *Suppose that there is a  $t_0 > 0$  such that if  $t > t_0$  then there is no critical point of  $d_{m_0}$  on any good component  $\Sigma_t$  of  $S_t$ . Then  $M$  has finite topological type.*

*Proof.* – Let  $E$  be an end of  $M$ . We know that there is a normalized ray  $\gamma$  such that  $\gamma(0) = m_0$  and  $\gamma$  exits  $E$ . Let  $U$  be the unbounded component of  $M - \overline{B}_{t_0}$  containing  $\{\gamma(t)\}_{t > t_0}$ . By assumption, for all  $t > t_0$ , the connected component  $\Sigma_t$  of  $S_t$  which contains  $\gamma(t)$  does not include any critical points of  $d_{m_0}$ . By the isotopy lemma [3, Lemma 1.4], for each  $t > t_0$  there is some  $\varepsilon > 0$  so that a neighborhood of  $\Sigma_t$  is homeomorphic to  $(t - \varepsilon, t + \varepsilon) \times \Sigma_t$ , the first coordinate being the distance from  $m_0$ . By compactness, for any  $b > a > t_0$ , we get an embedding  $[a, b] \times \Sigma_a \rightarrow U$ . Stacking these together, we get an embedding  $\psi : (t_0, \infty) \times \Sigma \rightarrow U$  for a fixed  $\Sigma$ . As the image of  $\psi$  is relatively open and closed, we obtain that  $U$  is homeomorphic to  $(0, \infty) \times \Sigma$  (compare [3, p. 35]). Furthermore,  $\Sigma$  is a closed connected topological manifold [3, Lemma 1.4]. In particular, for all  $t > t_0$ ,  $U \cap S_t$  is connected and good, so  $U$  does not contain any critical points. Thus  $M - \overline{B}_{t_0}$  does not contain any critical points in its unbounded components.

A priori,  $M - \overline{B_{t_0}}$  may have an infinite number of bounded components. However, as distance balls in  $M$  are precompact, it follows that only a finite number of these bounded components can intersect  $S_{t_0+1}$ . Thus there is some  $t_1 > t_0$  such that  $M - \overline{B_{t_1}}$  does not have any critical points, from which the lemma follows.  $\square$

*Remark.* – In fact, the proof above shows that  $M$  is homeomorphic to the interior of a compact topological manifold-with-boundary  $N$ . It follows from smoothing theory that if  $\dim(M) \geq 6$  then  $M$  is diffeomorphic to the interior of a compact smooth manifold-with-boundary. This is basically because one can put a smooth structure on  $\partial N$  if one can lift the classifying map for the tangent (micro)bundle from  $[\partial N, BTop]$  to  $[\partial N, BO]$ . As the interior of  $N$  is smooth, we can deform the lifting obstruction into the interior of  $N$ , where it vanishes.

Define

$$(25) \quad \mathcal{D}(m_0, t) = \sup \text{Diam}(\Sigma_t),$$

where the supremum is taken over all good components  $\Sigma_t$  of  $S_t$  and the diameter is measured using the metric on  $M$ . We claim that if the manifold has lower quadratic curvature decay and if

$$(26) \quad \lim_{t \rightarrow \infty} \frac{\mathcal{D}(m_0, t)}{t} = 0$$

there is a  $t_0 > 0$  such that if  $t > t_0$  then there is no critical point of  $d_{m_0}$  on any good component  $\Sigma_t$  of  $S_t$ . For a pair of points  $p, q \in M$ , define

$$e_{pq}(x) = d(p, x) + d(q, x) - d(p, q).$$

Clearly, for any  $t > 0$  and any point  $m \in M - B_{2t}$  on a ray from  $m_0$  which intersects  $\Sigma_t$ ,

$$(27) \quad e_{m_0 m}(x) \leq 2\mathcal{D}(m_0, t) \quad \text{for } x \in \Sigma_t.$$

By assumption, the sectional curvature on  $M - B_{t/2}$  satisfies

$$(28) \quad K_M \geq -\frac{4C}{t^2}.$$

Assume that there is a  $t_0 > 0$  such that for  $t > t_0$ ,

$$(29) \quad \mathcal{D}(m_0, t) \leq \frac{t}{4\lambda\sqrt{C}},$$

where  $\lambda$  is a large constant which will be specified later.

Suppose that  $x \in \Sigma_t$  is a critical point of  $d_{m_0}$ . (See Fig. 1.) Take a minimizing geodesic  $\tau$  from  $x$  to  $m$ . There is a minimizing geodesic  $\sigma$  from  $x$  to  $m_0$  such that  $\angle(\dot{\sigma}(0), \dot{\tau}(0)) \leq \frac{\pi}{2}$ . Take two points  $p = \sigma(a)$  and  $q = \tau(a)$  where  $a = t/(\lambda\sqrt{C})$ . By the triangle inequality, we have

$$(30) \quad e_{pq}(x) \leq e_{m_0 m}(x) \leq 2\mathcal{D}(m_0, t).$$

For  $\lambda \geq 100/\sqrt{C}$ , we see that the triangle  $\Delta_{pqx}$  is contained in a small neighborhood of  $x$  inside  $M - B_{t/2}$ . Then we can apply the Toponogov inequality to  $\Delta_{pqx}$  and obtain

$$(31) \quad \cosh(c_0 d(p, q)) \leq \cosh^2(c_0 a),$$

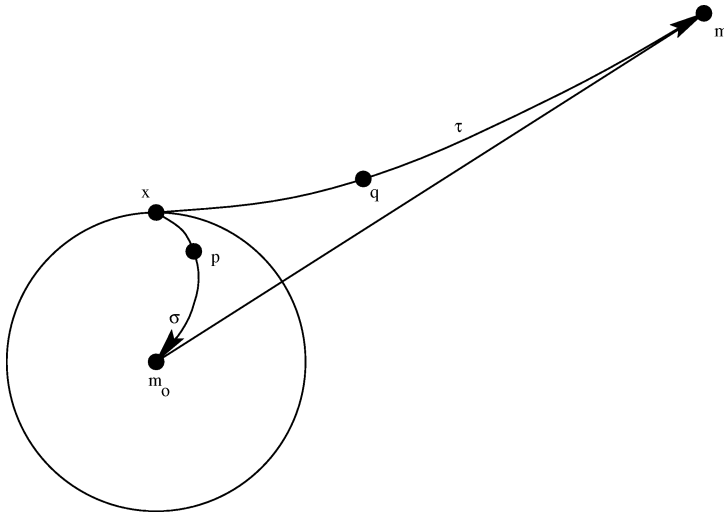


Fig. 1.

where  $c_0 = 2\sqrt{C}/t$ . Note that

$$(32) \quad c_0 d(p, q) = c_0 [2a - e_{pq}(x)] \geq 2c_0 [a - \mathcal{D}(m_0, t)] \geq \frac{3}{\lambda}.$$

We obtain

$$(33) \quad \cosh\left(\frac{3}{\lambda}\right) \leq \cosh^2\left(\frac{2}{\lambda}\right).$$

This is impossible for sufficiently large  $\lambda$ .

Finally, we must show that if  $\text{vol}(B_t) = o(t^2)$  and if there is a  $v > 0$  such that  $\text{vol}(B_1(x)) > v$  for all  $x \in M$ , then (29) holds for large  $t$ .

Let  $\Sigma_t$  be a connected component of the boundary of an unbounded component of  $M - B_t$ . For any  $x, y \in \Sigma_t$ , there is a continuous curve  $c: [0, r] \rightarrow \Sigma_t$  from  $x$  to  $y$ . Suppose that  $d(x, y) > 2$ . Then there is a partition  $0 = t_0 < t_1 < \dots < t_k = r$  such that  $\{B_1(c(t_i))\}_{i=0}^k$  are disjoint and  $B_2(c(t_i)) \cap B_2(c(t_{i+1})) \neq \emptyset$ . Note that  $B_1(c(t_i)) \subset B_{t+1} - \overline{B_{t-1}}$ . We have

$$(34) \quad (k + 1)v \leq \sum_{i=0}^k \text{vol}(B_1(c(t_i))) \leq \text{vol}(B_{t+1} - \overline{B_{t-1}}) \leq C_0 \frac{\text{vol}(B_{t-1})}{t - 1}.$$

Thus

$$(35) \quad \text{Diam}(\Sigma_t) \leq \sum_{i=0}^{k-1} d(c(t_i), c(t_{i+1})) \leq C_1 \frac{\text{vol}(B_{t-1})}{t - 1},$$

giving

$$(36) \quad \lim_{t \rightarrow \infty} \frac{\mathcal{D}(m_0, t)}{t} = 0.$$

This proves Proposition 1.1.  $\square$



**4. Proof of Proposition 1.2 and Corollary 1.1**

Fix an open set  $\mathcal{O}$  containing  $E$  which is diffeomorphic to  $(0, \infty) \times X$ . For  $u > 1$ , let  $\widehat{M}$  denote  $M$  with the metric  $u^{-2}g_M$ . Let  $\widehat{\mathcal{O}}$  denote the copy of  $\mathcal{O}$  in  $\widehat{M}$ . Let  $\widehat{B}_t$  and  $\widehat{S}_t$  denote the metric ball and metric sphere in  $\widehat{M}$  around  $m_0$ . Rescaling (1), there is a constant  $C' > 0$  such that the region  $\widehat{B}_{100} - \widehat{B}_{1/100}$  has sectional curvatures bounded by  $C'$ , uniformly in  $u$ . Put

$$(37) \quad T_{1/10}(\widehat{S}_1 \cap \widehat{\mathcal{O}}) = \{\widehat{m} \in \widehat{M} : d(\widehat{m}, \widehat{S}_1 \cap \widehat{\mathcal{O}}) \leq 1/10\}.$$

By [6, Theorem 0.1], there is a constant  $C'' > 0$  independent of  $u$  such that there is a connected codimension-0 submanifold  $U_u$  of  $\widehat{M}$  with

$$(38) \quad (\widehat{S}_1 \cap \widehat{\mathcal{O}}) \subset U_u \subset T_{1/10}(\widehat{S}_1 \cap \widehat{\mathcal{O}}),$$

$$(39) \quad \text{vol}(\partial U_u) \leq C'' \text{vol}(T_{1/10}(\widehat{S}_1 \cap \widehat{\mathcal{O}}))$$

and

$$(40) \quad \|\Pi_{\partial U_u}\| \leq C'',$$

where  $\Pi_{\partial U_u}$  is the second fundamental form of  $\partial U_u$  in  $\widehat{M}$ . Then by the Gauss–Codazzi equation, the intrinsic sectional curvature of  $\partial U_u$  is uniformly bounded in  $u$ . Rescaling to  $M$ , we have

$$(41) \quad \text{vol}(T_{1/10}(\widehat{S}_1 \cap \widehat{E})) = u^{-n} \text{vol}(T_{u/10}(S_u \cap \mathcal{O})) \leq u^{-n} \text{vol}(B_{11u/10}).$$

Let  $\{u_j\}_{j=1}^\infty$  be a sequence in  $\mathbb{R}^+$  approaching infinity such that

$$(42) \quad \lim_{j \rightarrow \infty} \text{vol}(B_{11u_j/10})/u_j^n = 0.$$

For  $j$  large, let  $Y_j$  be a connected component of  $\partial U_{u_j}$ . Let  $\mathcal{O}_j$  be the oriented cobordism between  $Y_j$  and  $X$  coming from the unbounded component of  $M - Y_j$  corresponding to  $E$ , truncated at some level  $\{R_j\} \times X$ . Let  $i : Y_j \rightarrow \mathcal{O}_j$  be the inclusion and let  $\pi : \mathcal{O}_j \rightarrow (0, \infty) \times X \rightarrow X$  be projection. Then

$$(43) \quad \int_X \omega \cup \prod_k p_{i_k}(TX) - \int_{Y_j} (\pi \circ i)^* \omega \cup \prod_k p_{i_k}(TY_j) = \int_{\mathcal{O}_j} d\left(\pi^* \omega \wedge \prod_k p_{i_k}(T\mathcal{O}_j)\right) = 0.$$

From (39), (41), (42) and [10, p. 37], we have that  $\int_{Y_j} (\pi \circ i)^* \omega \cup \prod_k p_{i_k}(TY_j) = 0$  if  $j$  is large enough. This proves Proposition 1.2.

Take  $\omega = 1 \in H^0(X; \mathbb{R})$ . Applying Proposition 1.2 to the Hirzebruch  $L$ -class, we obtain that the signature of  $X$  vanishes. Suppose  $X$  has a nonzero simplicial volume. Then the fundamental class  $[X] \in H^{n-1}(X; \mathbb{R})$  is a bounded cohomology class and Proposition 1.2 implies that  $\int_X \omega = 0$ , which is a contradiction. This proves Corollary 1.1.

**5. Proof of Proposition 1.3**

Suppose that  $\{g(t)\}_{t \in [1, \infty)}$  is a smooth 1-parameter family of Riemannian metrics on  $X$  with sectional curvatures that are uniformly bounded in  $t$ . Then one can check that  $dt^2 + t^2 g(t)$

is a metric of quadratic curvature decay on  $[1, \infty) \times X$  if  $\|g^{-1}(t) dg/dt\|_\infty = O(1/t)$  and  $\|g^{-1}(t) d^2g/dt^2\|_\infty = O(1/t^2)$ . Put  $\delta = t^{-1}$  and let  $g(t)$  be the Riemannian metric on  $X$  defined in [5, Section 3]. Then  $\{g(t)\}_{t \in [1, \infty)}$  has uniformly bounded sectional curvature in  $t$ . We claim that  $\|g^{-1}(t) dg/dt\|_\infty = O(1/t)$  and  $\|g^{-1}(t) d^2g/dt^2\|_\infty = O(1/t^2)$ . The metric  $g(t)$  is defined by a finite recursive process. One starts with an invariant Riemannian metric  $g_0$  for the  $F$ -structure and puts  $g_1(t) = \log^2(1+t)g_0$ . Clearly  $\|g_1^{-1}(t) dg_1/dt\|_\infty = O(1/t)$  and  $\|g_1^{-1}(t) d^2g_1/dt^2\|_\infty = O(1/t^2)$ . Then

$$(44) \quad g_{j+1}(t) = \begin{cases} \rho_j^2 g_j'(t) + h_j(t), & \text{on } U_j, \\ g_j(t), & \text{on } X - U_j, \end{cases}$$

where

- (1)  $U_j$  is a certain open subset of  $X$ ,
- (2)  $g_j'(t)$  is the part of  $g_j(t)$  corresponding to tangent vectors to the  $F$ -structure on  $U_j$ ,
- (3)  $h_j(t)$  is the part of  $g_j(t)$  corresponding to normal vectors to the  $F$ -structure on  $U_j$  and
- (4)  $\rho_j = t^{-\log(f_j)/\log(1/2)}$  with  $f_j : X \rightarrow [1/2, 1]$  a certain smooth function which is identically one on  $X - U_j$ .

It follows by induction on  $j$  that there is a metric of quadratic curvature decay and small volume growth on  $[1, \infty) \times X$ . Gluing  $[1, \infty) \times X$  onto  $N$ , we obtain the desired metric on  $M$ .

### 6. Proof of Proposition 1.4

If  $n$  is even then  $S^{n-1}$  has a polarized  $F$ -structure coming from a free  $S^1$ -action and the result follows from Proposition 1.3. The first nontrivial case is when  $n = 3$ .

Suppose that  $n = 3$ . By [4, Example 1.4], there is a metric  $h$  on  $\mathbb{R}^3$  with finite volume and bounded sectional curvature. Our metric will be conformally related to  $h$ . Let us first give the construction of  $h$  in detail. For  $j \in \mathbb{Z}^+$ , let  $C_j$  be the complement of a small solid torus in a solid torus. (See Fig. 2.) Then topologically,

$$(45) \quad \mathbb{R}^3 = (S^1 \times D^2) \cup_{T^2} C_1 \cup_{T^2} C_2 \cup_{T^2} \dots$$

We take  $m_0 \in S^1 \times D^2$ . Each  $C_j$  can be decomposed as  $C_j = (\Sigma_{2j} \times S_{2j}^1) \cup_{T^2} (\Sigma_{2j+1} \times S_{2j+1}^1)$ , where  $\Sigma_{2j}$  is a 2-sphere with three disks removed,  $\Sigma_{2j+1}$  is a 2-disk and  $S_{2j}^1, S_{2j+1}^1$  are circles. (See Fig. 3. Each block is to be rotated around the axis and then have its left and right faces

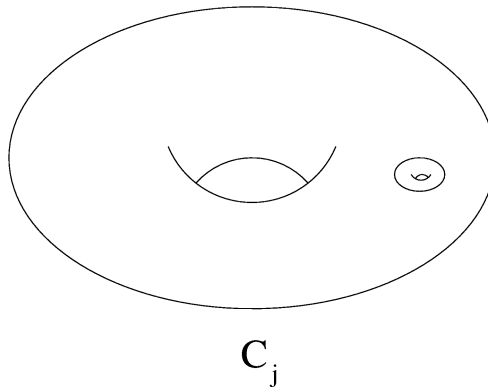


Fig. 2.

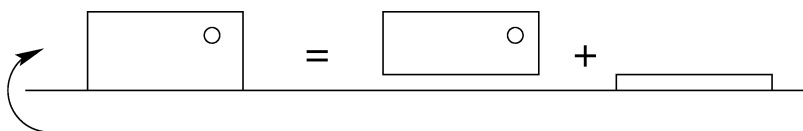


Fig. 3.

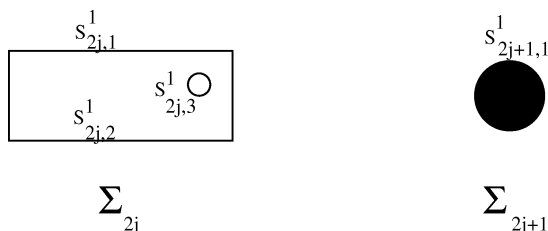


Fig. 4.

identified.) Put  $\partial\Sigma_{2j} = S_{2j,1}^1 \cup S_{2j,2}^1 \cup S_{2j,3}^1$ , where  $S_{2j,1}^1$  is the top side of the rectangle,  $S_{2j,2}^1$  is the bottom side of the rectangle and  $S_{2j,3}^1$  is the circle enclosing the removed disk. (See Fig. 4.) Put  $\partial\Sigma_{2j+1} = S_{2j+1,1}^1$ . The identifications of the toroidal boundaries are

$$(46) \quad \begin{aligned} S_{2j+1,1}^1 \times S_{2j+1}^1 &\sim S_{2j,2}^1 \times S_{2j}^1, \\ S_{2j,3}^1 \times S_{2j}^1 &\sim S_{2j-2,1}^1 \times S_{2j-2}^1, \end{aligned}$$

where

$$(47) \quad \begin{aligned} S_{2j+1,1}^1 &\sim S_{2j}^1, \\ S_{2j+1}^1 &\sim S_{2j,2}^1, \\ S_{2j,3}^1 &\sim S_{2j-2}^1, \\ S_{2j}^1 &\sim S_{2j-2,1}^1. \end{aligned}$$

We will put product metrics on  $\Sigma_{2j} \times S_{2j}^1$  and  $\Sigma_{2j+1} \times S_{2j+1}^1$ . Let  $\varepsilon_i$  be the length of  $S_i^1$  and let  $\delta_{i,*}$  be the length of  $S_{i,*}^1$ . Then (47) gives the relations

$$(48) \quad \delta_{2j,1} = \varepsilon_{2j+2}, \quad \delta_{2j,2} = \varepsilon_{2j+1}, \quad \delta_{2j,3} = \varepsilon_{2j-2}, \quad \delta_{2j+1,1} = \varepsilon_{2j}.$$

We will take  $\varepsilon_i = e^{-i}$ . Let  $\Sigma_\infty$  be a thrice-punctured sphere with a Riemannian metric such that three ends  $E_1, E_2, E_3 \cong (1, \infty) \times S^1$  are isometric to  $dr^2 + e^{-2r} d\theta^2$ . Put  $\Sigma_0 = \Sigma_\infty - (E_1 \cup E_2 \cup E_3)$ . Let  $u \in C^\infty([0, 1])$  be a nondecreasing function such that

$$(49) \quad u(s) = \begin{cases} s & \text{if } s \in [0, 1/3], \\ 1 & \text{if } s \in [1/2, 1]. \end{cases}$$

Given  $k \in \mathbb{Z}^+$ , put  $E(k) = [0, k] \times S^1$  with the metric  $dr^2 + e^{-2ku(r/k)} d\theta^2$ . Then put

$$(50) \quad \Sigma_{2j} = \Sigma_0 \cup_{\partial\Sigma_0} (E(2j+2) \cup E(2j+1) \cup E(2j-2)),$$

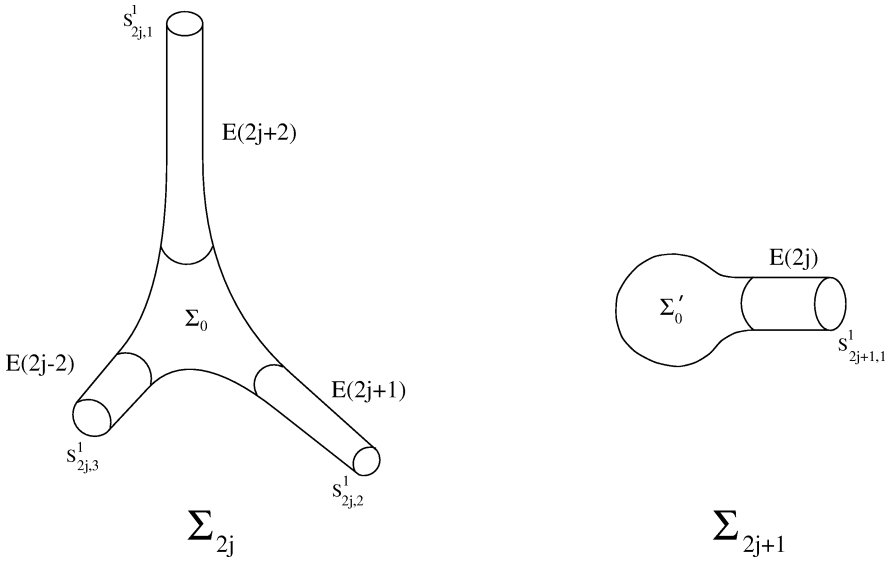


Fig. 5.

isometrically. (See Fig. 5.) Similarly, let  $\Sigma'_\infty$  be a once-punctured sphere with a Riemannian metric such that the end  $E \cong (1, \infty) \times S^1$  is isometric to  $dr^2 + e^{-2r} d\theta^2$ . Put  $\Sigma'_0 = \Sigma'_\infty - E$  and

$$(51) \quad \Sigma_{2j+1} = \Sigma'_0 \cup_{S^1} E(2j),$$

isometrically. (See Fig. 5.) Then one can check that  $\{\Sigma_i\}_{i=1}^\infty$  have uniformly bounded volume and curvature. Glue together the product metrics on  $\{\Sigma_{2j} \times S^1_{2j}\}_{j=1}^\infty$  and  $\{\Sigma_{2j+1} \times S^1_{2j+1}\}_{j=1}^\infty$  to give the metric  $h$  on  $\mathbb{R}^3$ . As  $\sum_{j=1}^\infty e^{-j} < \infty$ , it follows that  $h$  has bounded curvature and finite volume.

Given  $\phi \in C^\infty(\mathbb{R}^3)$ , put  $g = e^{2\phi}h$ . By (7), the weighted sectional curvatures

$$(52) \quad \{e^{2\phi(m)} |K(P, g)|\}_{m \in M, P \subset T_m M}$$

are uniformly bounded provided that the gradient  $\nabla\phi$  of  $\phi$  and the Hessian  $H(\phi)$  of  $\phi$  are uniformly bounded with respect to  $h$ .

We construct  $\phi$  on  $\Sigma_{2j} \times S^1_{2j}$  and  $\Sigma_{2j+1} \times S^1_{2j+1}$  to be the pullbacks of functions on  $\Sigma_{2j}$  and  $\Sigma_{2j+1}$ , respectively. Let  $\phi_\infty \in C^\infty(\Sigma_\infty)$  be a Morse function with one critical point, of saddle type, such that

$$(53) \quad \begin{aligned} \phi_\infty|_{E_1} &= 40d(\cdot, \Sigma_0), \\ \phi_\infty|_{E_2} &= 10d(\cdot, \Sigma_0), \\ \phi_\infty|_{E_3} &= -80 - 40d(\cdot, \Sigma_0), \\ \phi_\infty(\Sigma_0) &\subset [-80, 0]. \end{aligned}$$

Then in terms of (50), put

$$(54) \quad \phi|_{\Sigma_{2j}} = 80j^2 + 80j + \phi_\infty|_{\Sigma_{2j}}.$$

(See Fig. 6.) Similarly, let  $\phi'_\infty \in C^\infty(\Sigma'_\infty)$  be a Morse function with one critical point, a local

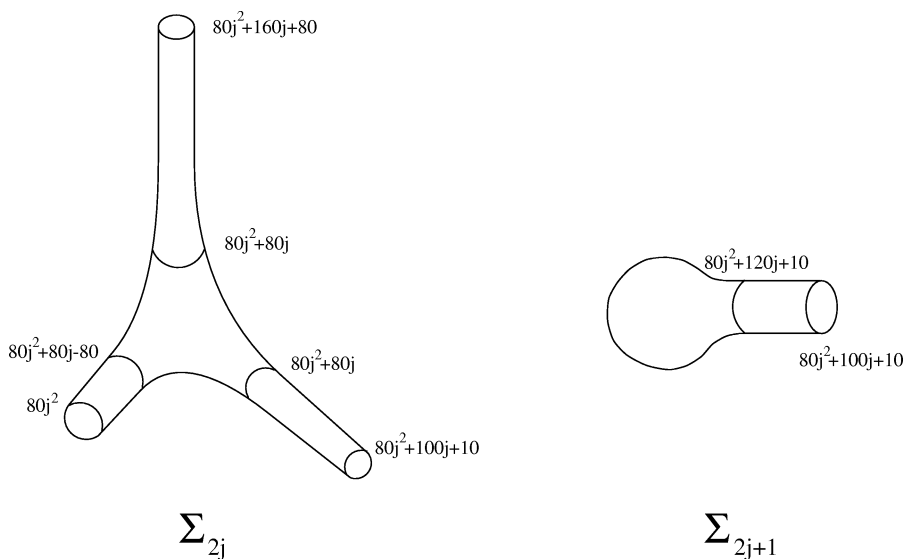


Fig. 6.

maximum, such that

$$(55) \quad \phi'_\infty|_E = -10d(\cdot, \Sigma'_j), \quad \phi'_\infty(\Sigma'_j) \subset [0, 10].$$

Then in terms of (51), put

$$(56) \quad \phi|_{\Sigma_{2j+1}} = 80j^2 + 120j + 10 + \phi'_\infty|_{\Sigma_{2j+1}}.$$

(See Fig. 6.) Finally, define  $\phi$  on the  $S^1 \times D^2$  factor in (45) so as to extend  $\phi$  to a smooth function on  $\mathbb{R}^3$ .

It is easy to see that  $\nabla\phi$  and  $H(\phi)$  are uniformly bounded on  $\mathbb{R}^3$ . As

$$(57) \quad d_g(m_0, m)^2 |K(P, g)| = \frac{d_g(m_0, m)^2}{e^{2\phi(m)}} e^{2\phi(m)} |K(P, g)|,$$

in order to show that  $g$  has quadratic curvature decay, it suffices to show that  $e^{-\phi(m)}d_g(m_0, m)$  is uniformly bounded with respect to  $m \in \mathbb{R}^3$ . Let  $T^2$  be the first torus factor in (45). Then it suffices to show that  $e^{-\phi(m)}d_g(T^2, m)$  is uniformly bounded with respect to  $m \in \mathbb{R}^3$ . Let  $\{\gamma(s)\}_{s \in [0, t]}$  be a piecewise smooth path from  $m$  to  $T^2$  which is unit-speed with respect to  $h$ , and along which  $\phi$  is nonincreasing. Then letting  $L_g(\gamma)$  denote the length of  $\gamma$  with respect to  $g$ , we have

$$(58) \quad e^{-\phi(m)}d_g(T^2, m) \leq e^{-\phi(m)}L_g(\gamma) = \int_0^t e^{\phi(\gamma(s)) - \phi(m)} ds.$$

We take  $\gamma$  to be (reparametrized) gradient flow of  $\phi$  starting from  $m$ . Although  $\phi$  is not a Morse function, we note that gradient flow on  $\Sigma_{2j} \times S^1_{2j}$  is essentially the same as gradient flow on  $\Sigma_{2j}$ , as it is constant in the  $S^1_{2j}$ -factor, and gradient flow on  $\Sigma_{2j+1} \times S^1_{2j+1}$  is essentially the same as gradient flow on  $\Sigma_{2j+1}$ , as it is constant in the  $S^1_{2j+1}$ -factor. If the projection of  $\gamma$  onto  $\Sigma_{2j}$  or

$\Sigma_{2j+1}$  meets a critical point  $c$  of saddlepoint type, we extend  $\gamma$  beyond  $c$  to become a piecewise smooth curve with a corner, again following a downward gradient trajectory. We continue this process until  $\gamma$  hits  $T^2$ . Changing variable to  $u = \phi(\gamma(s))$ , we have

$$(59) \quad \int_0^t e^{\phi(\gamma(s)) - \phi(m)} \, ds = \int_{80}^{\phi(m)} e^{u - \phi(m)} \frac{du}{|\nabla\phi|(\phi^{-1}(u))}.$$

As  $\phi(\gamma(s))$  is nonincreasing, if  $m \in C_j$  then  $\gamma$  never enters  $\Sigma_{2k+1} \times S_{2k+1}^1$  for  $k < j$ . Also  $\gamma$  hits at most one critical point in each  $\Sigma_{2k}$  for  $k < j$ . By the construction of  $\phi$ , if  $c_k \in \Sigma_{2k}$  is the critical point then  $\phi|_{c_k \times S_{2k}^1} \in [80k^2 + 80k - 80, 80k^2 + 80k]$ . Thus the singularities of  $1/|\nabla\phi|(\phi^{-1}(u))$  are well-spaced in  $u$ . If  $\gamma$  passes through a critical point  $c$  and  $u_0 = \phi(c)$  then

$$\frac{1}{|\nabla\phi|(\phi^{-1}(u))} \sim \frac{1}{\sqrt{|u - u_0|}}$$

for  $u \sim u_0$ . From the uniform nature of  $\nabla\phi$  near the critical points, it follows that there is a constant  $D > 0$ , independent of  $m \in \mathbb{R}^3$ , such that for all  $x \in [80, \phi(m) - 1]$ ,

$$(60) \quad \int_x^{x+1} \frac{du}{|\nabla\phi|(\phi^{-1}(u))} \leq D.$$

Then

$$(61) \quad \int_{80}^{\phi(m)} e^{u - \phi(m)} \frac{du}{|\nabla\phi|(\phi^{-1}(u))} \leq \frac{D}{1 - e^{-1}}.$$

Thus  $g$  has quadratic curvature decay.

Put  $t_{j+1} = d(m_0, C_{j+1})$ . For  $j > 0$ , each path from  $m_0$  to  $C_{j+1}$  must pass through  $C_j$ . Put

$$(62) \quad D_j = (S^1 \times D^2) \cup_{T^2} C_1 \cup_{T^2} \dots \cup_{T^2} C_j.$$

Then  $B_{t_{j+1}}(m_0) \subset D_j$  and so  $\text{vol}(B_{t_{j+1}}) \leq \text{vol}(D_j)$ . With respect to (50), let  $F_j$  be the subset  $[j + 2, 2j + 2] \times S_{2j}^1 \subset E(2j + 2) \times S_{2j}^1$ . (See Fig. 7.) For large  $j$ ,  $\phi|_{D_j - F_j} \leq 80j^2 + 120j + 80$  and so

$$(63) \quad \text{vol}(D_j - F_j) \leq e^{240j^2 + 360j + 240} \text{vol}(\mathbb{R}^3, h).$$

On the other hand,

$$(64) \quad \text{vol}(F_j) = \int_{j+2}^{2j+2} e^{3(80j^2 + 80j + 40x)} e^{-2(2j+2)} \, dx = \frac{1 - e^{-120j}}{120} e^{240j^2 + 480j + 240} e^{-2(2j+2)}.$$

Thus

$$(65) \quad \text{vol}(B_{t_{j+1}}) = O(e^{240j^2 + 480j + 240} e^{-2(2j+2)}).$$

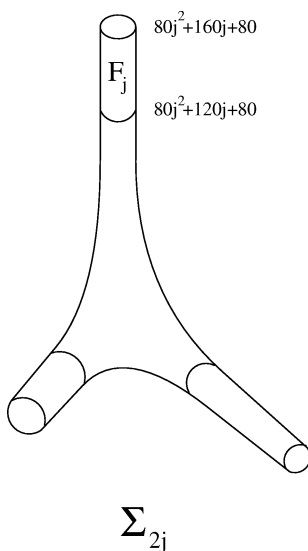


Fig. 7.

As any path from  $m_0$  to  $C_{j+1}$  must pass through  $F_j$ ,

$$(66) \quad t_{j+1} \geq \int_{j+2}^{2j+2} e^{80j^2+80j+40x} dx = \frac{1 - e^{-40j}}{40} e^{80j^2+160j+80}.$$

Thus

$$(67) \quad \text{vol}(B_{t_{j+1}})/t_{j+1}^3 = O(e^{-2(2j+2)}),$$

showing that  $g$  has slow volume growth.

If  $n > 3$ , we can do a similar construction in which  $C_j$  is the complement of a small  $T^{n-2} \times D^2$  in  $T^{n-2} \times D^2$  and  $C_j$  is decomposed as  $(\Sigma_{2j} \times T^{n-2}) \cup_{T^{n-1}} (\Sigma_{2j+1} \times T^{n-2})$ .

### 7. Proof of Corollary 1.2

(1) If  $n = 2$ , put a metric on  $\text{Int}(N)$  with flat cylindrical ends.

(2) If  $n = 3$ , suppose that  $\partial N$  consists of 2-spheres and 2-tori. For a 2-sphere component of  $\partial N$ , put a metric coming from Proposition 1.4 on the corresponding end of  $\text{Int}(N)$ . For a 2-torus component of  $\partial N$ , put a flat metric on the corresponding end  $(1, \infty) \times T^2$  of  $\text{Int}(N)$ . This gives the desired metric on  $\text{Int}(N)$ . Now suppose that  $\text{Int}(N)$  has a metric with quadratic curvature decay and slow volume growth. From Corollary 1.1, the simplicial volume of  $\partial N$  must vanish. Thus  $\partial N$  consists of 2-spheres and 2-tori.

(3) If  $n = 4$ , suppose that the connected components of  $\partial N$  are graph manifolds. Then  $\partial N$  has a polarized  $F$ -structure and Proposition 1.3 implies that there is a metric on  $\text{Int}(N)$  with quadratic curvature decay and slow volume growth. Now suppose that Thurston's Geometrization Conjecture holds and that  $\text{Int}(N)$  has a metric with quadratic curvature decay and slow volume growth. From Corollary 1.1, the simplicial volume of  $\partial N$  must vanish. From [12], this implies that the connected components of  $\partial N$  are graph manifolds.

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