"BUBBLING" OF THE PRESCRIBED CURVATURE FLOW ON THE TORUS

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Abstract. By a classical result of Kazdan-Warner, for any smooth sign-changing function $f$ with negative mean on the torus $(M, g_b)$ there exists a conformal metric $g = e^{2u}g_b$ Gauss curvature $K_g = f$, which can be obtained from a minimizer $u$ of Dirichlet’s integral in a suitably chosen class of functions. As shown by Galimberti, these minimizers exhibit "bubbling" in a certain limit regime. Here we sharpen Galimberti’s result by showing that all resulting “bubbles” are spherical. Moreover, we prove that analogous “bubbling” occurs in the prescribed curvature flow.

1. Background and results

1.1. The Kazdan-Warner result. Let $(M, g_b)$ be a closed surface of genus zero. A classical result of Kazdan-Warner [15] characterizes those smooth functions $f$ on $M$ for which there exists a conformal metric $g = e^{2u}g_b$ on $M$ with Gauss curvature $K_g = f$. By the uniformization theorem, with no loss of generality we may assume that the background metric $g_b$ is flat with $K_{g_b} = 0$ and has volume $vol(M, g_b) = 1$.

In view of the Gauss equation

\[
K_g = e^{-2u}(-\Delta g_b u + K_{g_b}) = -e^{-2u}\Delta g_b u
\]

we are then led to study the equation

\[
-\Delta g_b u = fe^{2u} \text{ on } M. \tag{1.2}
\]

**Theorem 1.1.** (Kazdan-Warner [14]) There exists a solution $u$ of (1.2) if and only if either $f \equiv 0$, or if the function $f$ changes sign and satisfies

\[
\int_M f d\mu_{g_b} < 0. \tag{1.3}
\]

Leaving aside the trivial case when $f \equiv 0$ with corresponding solution $u \equiv 0$ of (1.2), in the case when $f$ changes sign and satisfies (1.3) a solution $u$ to (1.2) may be obtained by minimizing the Liouville energy (or Dirichlet integral)

\[
E(u) = \frac{1}{2} \int_M |\nabla u|_{g_b}^2 \, d\mu_{g_b}
\]

in the class of functions

\[
C = C_f = \{ u \in H^1(M, g_b) : \int_M fe^{2u} \, d\mu_{g_b} = 0 \}.
\]

Observe that the constraint

\[
\int_M f \, d\mu_g = \int_M fe^{2u} \, d\mu_{g_b} = 0, \tag{1.4}
\]

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1
where \( g = e^{2u}g_b \), is natural in view of (1.2) or the Gauss-Bonnet theorem.

Since both the energy \( E(u) \) and the constraint (1.4) are left unchanged if we replace a function \( u \in C \) with \( u + c \) for any \( c \in \mathbb{R} \), in order to show existence of a minimizer for \( E \) in \( C \) traditionally one restricts attention to comparison functions \( u \in C \) with vanishing mean; see for instance Chang [6], pp. 2-4. However, normalizing the volume

\[
\text{vol}(M, g) = \int_M e^{2u} \, d\mu_g = 1 = \text{vol}(M, g_b)
\]

of comparison functions will work equally well.

1.2. “Bubbling” metrics. Following the argument of [1] for surfaces of genus larger than one, Galimberti [12] showed “bubbling” of the Kazdan-Warner metrics in a certain limit regime. To describe his results, let \( f_0 \) be a smooth, non-constant function with \( \max_{p \in M} f_0(p) = 0 \), and for any \( \lambda \in \mathbb{R} \) let \( f_\lambda = f_0 + \lambda \). Then for any sufficiently small \( \lambda > 0 \) the function \( f_\lambda \) changes sign and satisfies (1.3). By Theorem 1.1 therefore there exists a solution \( \hat{u}_\lambda \) of (1.2) which can be obtained as \( \hat{u}_\lambda = u_\lambda + c_\lambda \) from a minimizer \( u_\lambda \) of \( E \) in the set \( C_\lambda = C_{f_\lambda} \) satisfying (1.5).

Setting \( \beta_\lambda := E(u_\lambda) = \min\{E(u) \mid u \in C_\lambda\} \), then it follows from Theorem 1.1 that \( \beta_\lambda \to \infty \) as \( \lambda \downarrow 0 \); see also (4.3) below. Moreover, with a delicate argument Galimberti is able to show that \( \beta_\lambda \) is non-increasing as a function of \( \lambda \), which as in [1] then allows to control the total curvature of the metrics \( \hat{g}_\lambda = e^{2u_\lambda}g_b \) for suitable \( \lambda \downarrow 0 \) and to show that after rescaling the metrics suitably near local maximum points \( p_\lambda^{(1)} \) of \( u_\lambda \) one or more “bubbles” may be extracted from \( \hat{g}_\lambda \); see [12], Theorem 1.1.

One of our goals in the present paper is to better understand this bubbling behavior and to obtain the more precise characterization stated in Theorem 4.4 below. Section 4 of this paper, where we give the proof of this result, also contains a simplified proof of the crucial monotonicity property of \( \beta_\lambda \).

A second goal is to show that “bubbling” as \( \lambda \downarrow 0 \) not only can be observed for certain sequences of minimizers \( u_\lambda \) of \( E \) in \( C_\lambda \), but that an analogous behavior occurs along the prescribed curvature flow for suitably chosen initial data in \( C_\lambda \).

1.3. Prescribed curvature flow. Given a function \( f \) satisfying the assumptions of Theorem 1.1 for any \( u_0 \in C = C_f \) we study the equation

\[
u_t = \alpha f - K \quad \text{on } M \times [0, \infty[\
\]

with initial data \( u \big|_{t=0} = u_0 \), where \( K = K_g \) with \( g = g(t) = e^{2u(t)}g_b \) at any time \( t \geq 0 \) and where the function \( \alpha = \alpha(t) \) is determined so that \( u(t) \in C \) for all \( t \geq 0 \); that is, we require the condition

\[
\frac{1}{2} \frac{d}{dt} \left( \int_M f \, d\mu_g \right) = \int_M u_t f \, d\mu_g = \int_M (\alpha f - K) f \, d\mu_g = 0.
\]

Solving for \( \alpha \) then we find

\[
\alpha = \frac{\int_M f K \, d\mu_g}{\int_M f^2 \, d\mu_g}.
\]
The flow (1.6)-(1.7) is the negative $L^2$-gradient flow for $E$ on $\mathcal{C}$ with respect to the evolving metrics. Indeed, for a sufficiently smooth solution $u = u(t)$ of (1.6)-(1.7) on an interval $[0, T]$ there holds

$$\frac{d}{dt} E(u(t)) = -\int_M u_t \Delta_{g_t} u \, d\mu_{g_t} = \int_M (\alpha f - K) \, d\mu_g = -\int_M |u_t|^2 \, d\mu_g \leq 0. \quad (1.9)$$

Hence we also have the uniform a-priori bound

$$E(u(T)) + \int_0^T \int_M |u_t|^2 \, d\mu_g \, dt \leq E(u_0) \quad (1.10)$$

for any $T > 0$. Also note that by (1.4) and the Gauss-Bonnet theorem for a solution $u$ of (1.6)-(1.7) the volume is preserved with

$$\frac{1}{2} \frac{d}{dt} \text{vol}(M, g(t)) = \int_M u_t \, d\mu_g = \int_M f \, d\mu_g - \int_M K \, d\mu_g = 0. \quad (1.11)$$

Normalizing the initial data $g_0 = e^{2u_0} g_b$ to satisfy $\text{vol}(M, g_0) = 1$, then we have

$$\text{vol}(M, g) = \int_M d\mu_g = \int_M e^{2u} \, d\mu_{g_b} = 1 \quad (1.12)$$

for all $t > 0$, and we see that (1.6)-(1.7) induces a flow in the space

$$\mathcal{C}^* = \mathcal{C}_f^* = \{ u \in H^1(M, g_b) : \int_M f e^{2u} \, d\mu_{g_b} = 0, \int_M e^{2u} \, d\mu_{g_b} = 1 \}. \quad \text{Our interest in the study of (1.6)-(1.7) is inspired by recent work of Ngô and Xu [18] on a flow approach to the results of Escobar-Schoen [11] on the Kazdan-Warner [15] problem of prescribed scalar curvature on a closed Riemannian manifold of dimension $n \geq 3$ with vanishing Yamabe invariant. The following result is parallel to yet unpublished, independent results of Ngô and Xu [17].}

**Theorem 1.2.** Suppose that $f$ is smooth, changes sign, and satisfies (1.3). Then for any smooth $u_0 \in \mathcal{C}^*$ there exists a unique, global smooth solution $u$ of (1.6)-(1.7) with initial data $u|_{t=0} = u_0$ and satisfying $u(t) \in \mathcal{C}^*$ as well as the energy bound $E(u(t)) \leq E(u_0)$ for all $t$. Moreover, we have $u(t) \to u_\infty$ in $H^2(M, g_b)$ (and smoothly) as $t \to \infty$ suitably, where $u_\infty + c_\infty$ is a smooth solution of (1.2) for some $c_\infty \in \mathbb{R}$.

The remaining case when $f \equiv 0$ which is not covered by Theorem 1.2 corresponds to the 2-dimensional Ricci flow on $(M, g_b)$ for which Hamilton [13] established global existence and exponentially fast convergence. In fact, Hamilton [13] shows global existence and exponentially fast convergence of the Ricci flow on any closed surface $(M, g_b)$. For the sphere his work was completed by Chow [9]; see also [22] for a simpler proof of exponentially fast convergence in this case.

Also in the setting of Theorem 1.2 our Theorem 3.2 below shows that the convergence is exponentially fast when $u_\infty$ is a strict relative minimizer of $E$ in $\mathcal{C}^*$, which nicely complements the result of Hamilton [13] (where $u_\infty = 0$ for a flat background metric). Not surprisingly, we also have unconditional convergence of the flow when the solution of (1.2) is unique; see our Theorem 3.3 below. Moreover, with the help of the Łojasiewicz-Simon inequality Ngô and Xu [17] showed unconditional convergence of the prescribed curvature flow on the torus for any given analytic sign-changing function $f$ with negative average.
In contrast, the nature of convergence is not clear if $f$ is only assumed to be smooth (or even less regular), and in the final Section 6 of this paper we sketch an idea how “bubbling” of the prescribed curvature flow might give rise to infinitely many different subsequential limits of the flow as $t \to \infty$ in a certain limit regime.

It would be interesting to investigate the prescribed curvature flow also in the case when $f$ consists of a regular part and a sum of Dirac masses, where solutions of (1.2) would correspond to conical metrics of prescribed curvature with prescribed opening angles, as in the work of Troyanov [26] and, more recently, Carlotto-Malchiodi [4], or to study the heat flow for Chern-Simons vortices, as in the work of Tarantello [24], where a flow equation similar to (1.6), (1.7) may be expected to arise. A prescribed curvature flow in higher dimensions was introduced by Brendle [2].

The following Sections 2-3 contain the proof of Theorem 1.2 and of the convergence results Theorem 3.2 and 3.3 alluded to above. In Section 4 we then study “bubbling” in the time-independent case, before we analyze the “bubbling” behavior of the flow (1.6), (1.7) in Section 5.

I am indebted to Anh Ngô for helpful comments regarding the prescribed curvature flow, in particular, for pointing out the simple proof of Lemma 2.3.

2. Global existence of the prescribed curvature flow

Given a function $f$ as in Theorem 1.2 and smooth initial data $u_0 \in C^*$ we now show that we can find a unique smooth solution $u$ of (1.6)-(1.7) defined for all time.

Note that for any $u \in C^*$ Jensen’s inequality gives the bound

$$2\bar{u} := 2 \int_M u \, d\mu_{g_0} \leq \log \left( \int_M e^{2u} \, d\mu_{g_0} \right) = 0$$

for the average of $u$.

Next recall the following result of Trudinger [27], sharpened by Moser [16].

**Theorem 2.1.** Let $\Omega \subset \mathbb{R}^2$ be bounded. For any $\beta \leq 4\pi$ there holds

$$\sup \{ \int_{\Omega} e^{u^2} \, dx; \ u \in H^1_0(\Omega), \| \nabla u \|^2_{L^2} \leq \beta \} < \infty,$$

and the constant $\beta_0 = 4\pi$ is best possible.

In fact, for any bounded domain $\Omega \subset \mathbb{R}^2$, any $u \in H^1_0(\Omega)$ with $\| \nabla u \|^2_{L^2} \leq \beta < 4\pi$ it is not hard to see that

$$\frac{1}{\mu(\Omega)} \int_{\Omega} e^{u^2} \, dx \leq \frac{4\pi}{4\pi - \beta}.$$

Using a partition of unity one can obtain a similar result on any closed surface; see the lecture notes of Chang [6], or [4], Theorem 4.4, for reference.

**Theorem 2.2.** Let $(M, g_0)$ be closed and orientable. Then for any $\beta < 4\pi$ there holds

$$C_{TM}(\beta) = \sup \{ \int_M e^{u^2} \, d\mu_{g_0}; \ u \in H^1(M, g_0), \| \nabla u \|^2_{L^2} \leq \beta, \ \bar{u} = 0 \} < \infty.$$

Applying the bounds in Theorem 2.2 to a function $u \in H^1(M, g_0)$, and estimating

$$2|p(u - \bar{u})| \leq 2\pi (u - \bar{u})^2 / \| \nabla u \|^2_{L^2(M, g_0)} + \frac{p^2}{2\pi} \| \nabla u \|^2_{L^2(M, g_0)}$$
via Young’s inequality, for any \( p \in \mathbb{R} \) we then find
\[
\int_M e^{2p(u - \bar{u})} \, d\mu_{g_0} \leq C_{TM}(2\pi)e^{\frac{2}{2\pi}\|\nabla u\|_{L^2(M, g_0)}^2}.
\]

In particular, for any \( u \in H^1(M, g_0) \) satisfying \( 1.12 \) we can bound
\[
1 = \int_M d\mu_g = \int_M e^{2u} \, d\mu_{g_0} = e^{2\bar{u}} \int_M e^{2(u - \bar{u})} \, d\mu_{g_0} \leq Ce^{2\bar{u}}
\]
with a constant \( C = C(E(u)) \), and we conclude the uniform lower bound
\[
\bar{u} \geq -m_0
\]
for the average of \( u \) with some \( m_0 = m_0(E(u_0)) \). Moreover, for any \( p \in \mathbb{R} \) the bounds (2.3) and (2.4) together with (2.2) give
\[
\int_M e^{2pu} \, d\mu_{g_0} = e^{2\bar{u}} \int_\Omega e^{2p(u - \bar{u})} \, d\mu_{g_0} \leq C(p, E(u)).
\]

Throughout the remainder of this section suppose that \( u = u(t) \) solves \( 1.6 \)-\( 1.7 \) with initial data \( u(t=0) = u_0 \in C^* = C^*_f \) for some smooth, sign-changing function \( f \) on \( M \) satisfying \( 1.3 \). Note that by \( 1.10 \) the bounds (2.3), (2.4) then hold with uniform constants \( m_0 = m_0(E(u_0)) \), respectively.

**Lemma 2.3.** There exists a constant \( m_1 > 0 \) such that for all \( t > 0 \) there holds
\[
\int_M f^2 \, d\mu_g \geq m_1.
\]

**Proof.** By Hölder’s inequality, assumption \( 1.3 \), and (2.2) we have
\[
0 < | \int_M f \, d\mu_{g_0} |^2 \leq \int_M e^{-2u} \, d\mu_{g_0} \int_M f^2 e^{2u} \, d\mu_{g_0} \leq C \int_M f^2 \, d\mu_g,
\]
uniformly in \( t > 0 \).

As an immediate consequence we obtain the following result.

**Lemma 2.4.** There exists a constant \( \alpha_0 > 0 \) such that for all \( t > 0 \) there holds
\[
|\alpha| \leq \alpha_0.
\]

**Proof.** By \( 1.1 \) and \( 1.10 \) we can estimate
\[
| \int_M fK \, d\mu_{g_0} | = | \int_M f(-\Delta_{g_0} u) \, d\mu_{g_0} | \leq \int_M |\nabla f|_{g_0} |\nabla u|_{g_0} \, d\mu_{g_0}
\]
\[
\leq C \| f \|_{C^*} E^{1/2}(u) \leq CE^{1/2}(u_0) = : C_0.
\]

From \( 1.8 \) and Lemma 2.3 it then follows that
\[
|\alpha| \leq C_0m_1^{-1} = : \alpha_0,
\]
as claimed.

The above bounds suffice to show existence of a unique solution \( u \) to \( 1.6 \), \( 1.7 \) for all time. Indeed, using \( 1.1 \) to write equation \( 1.6 \) in the form
\[
u_t = \alpha f - K = \alpha f + e^{-2u} \Delta_{g_0} u = \alpha f + \Delta_{g_0} u,
\]
from Lemma 2.3 we conclude that
\[
|u_t - \Delta_{g_0} u| = |\alpha f| \leq |\alpha_0| \| f \|_{L^\infty} = : C_1,
\]
uniformly in $t > 0$, and by the maximum principle, applied to the function $u \pm C_1 t$, it follows that

\begin{equation}
(2.6) \quad \sup_M |u(t)| \leq \sup_M |u_0| + C_1 t
\end{equation}

for all $t > 0$. In particular, equation (1.7) is uniformly parabolic on any finite time interval; therefore, the unique local solution $u$ to (1.6), (1.7) that we can construct with the help of a standard fixed point argument (as explained in detail for instance in [4], Proposition 6.3) may be extended globally.

In fact, with the help of (1.10) we can turn (2.6) into a uniform estimate for all time. For convenience, let

\[ F = F(t) = \int_M |K - \alpha f|^2 \, d\mu_g, \quad G = G(t) = \int_M |\nabla (K - \alpha f)|^2 \, d\mu_g. \]

Then we have the following result.

**Lemma 2.5.** There holds $\sup_{t > 0} \|u(t)\|_{L^\infty} < \infty$.

**Proof.** By (1.10) we have

\[ \int_0^\infty F(t) \, dt \leq E(u_0) < \infty. \]

Hence for any $T > 0$ we can find $t_T \in [T, T + 1]$ such that

\[ F(t_T) = \inf_{T < t < T + 1} F(t) \leq E(u_0). \]

But then in view of the uniform bound $\|e^u\|_{L^6(M, g_0)} \leq C(3, E(u_0))$ from (2.4), and writing (1.1) in the form

\[ -\Delta_{g(t)} u = Ke^{2u} = (K - \alpha f)e^u \cdot e^u + \alpha f e^{2u}, \]

at time $t_T$, with uniform constants $C > 0$ by Hölder’s inequality we have

\[ \|\Delta_{g(t)} u\|_{L^{3/2}(M, g_0)} \leq \|(K - \alpha f)e^u\|_{L^2(M, g_0)} \|e^u\|_{L^6(M, g_0)} + C \leq C F(t_T)^{1/2} + C \leq C. \]

Elliptic regularity then yields

\[ \|u - \bar{u}\|_{L^\infty} \leq C \|\nabla^2 u\|_{L^{3/2}(M, g_0)} \leq C \|\Delta_{g(t)} u\|_{L^{3/2}(M, g_0)} \leq C, \]

and in view of (2.4) and (2.6) we conclude the uniform bound $\|u(t_T)\|_{L^\infty} \leq C$. Upon shifting time by $t_T$, from (2.6) we now find that

\begin{equation}
(2.7) \quad \sup_{T+1 \leq s \leq T+2} \|u(t)\|_{L^\infty} \leq \sup_{t_T \leq s \leq T+2} \|u(t)\|_{L^\infty} \leq \|u(t_T)\|_{L^\infty} + 2C_1 \leq C.
\end{equation}

Since $T > 0$ is arbitrary, the claim follows. \hfill \Box

Thus, in particular, the metrics $g(t)$ will be uniformly equivalent to the background metric $g_0$ for all $t > 0$. 
3. Convergence

In order to study convergence of the flow we consider the evolution of curvature. From (1.1) and (1.6) it follows that

\[(3.1) \quad K_t = \frac{d}{dt}(-e^{-2u} \Delta_g u) = -2u_t K - \Delta_g u_t = 2K(K - \alpha f) + \Delta_g(K - \alpha f).\]

Thus, and again using (1.6), we obtain

\[\frac{1}{2} \frac{d}{dt} \int_M |K - \alpha f|^2 \, d\mu_g = \int_M \left( (K_t - \alpha_t f)(K - \alpha f) - (K - \alpha f)^3 \right) d\mu_g \]

\[(3.2) = - \int_M |\nabla (K - \alpha f)|^2 \, d\mu_g + 2 \int_M K(K - \alpha f)^2 \, d\mu_g - \int_M (K - \alpha f)^3 \, d\mu_g \]

where we observe that the term involving \(\alpha_t\) vanishes due to (1.7). Using (1.9) to write \(\alpha f - K = u_t\) for brevity, by Hölder’s inequality we can bound the last term

\[\|u_t\|_{L^3(M,g)}^3 \leq \|u_t\|_{L^2(M,g)} \|u_t\|_{L^1(M,g)}.\]

In view of Lemma 2.15 by the Gagliardo-Nirenberg inequality then with uniform constants \(C > 0\) for any \(t > 0\) we have

\[\|u_t\|_{L^4(M,g)} \leq C \|u_t\|_{L^2(M,g)} \|u_t\|_{H^1(M,g)} \leq C \|u_t\|_{L^2(M,g)} \|u_t\|_{H^1(M,g)} \leq C \|u_t\|_{L^2(M,g)} \|u_t\|_{H^1(M,g)}.\]

Recalling the notation

\[F(t) = \int_M |u_t|^2 \, d\mu_g, \quad G(t) = \int_M |\nabla u_t|^2 \, d\mu_g = \int_M |\nabla u_t|_{g_0}^2 \, d\mu_{g_0},\]

by Young’s inequality finally we can bound

\[(3.3) \quad \|u_t\|_{L^3(M,g)}^3 \leq C \|u_t\|_{L^2(M,g)} \|u_t\|_{H^1(M,g)} \leq CF^2 + \frac{1}{2}(F + G).\]

Together with the uniform bound \(|\alpha f| \leq C_1\) from Lemma 2.14 equation (3.2) then gives the differential inequality

\[\frac{dF}{dt} + G \leq C_2 F + C_3 F^2 \quad \text{on } [0, \infty[\]

with uniform constants \(C_2 = 4C_1 + 1, C_3 > 0\).

**Lemma 3.1.** We have \(F(t) \to 0\) uniformly as \(t \to \infty\).

**Proof.** Recalling the bound

\[(3.5) \quad \int_0^\infty F(t) \, dt \leq E(u_0)\]

from (1.10), we have \(\liminf_{t \to \infty} F(t) = 0\). Hence there exist \(t_i \to \infty\) with \(F(t_i) \to 0\) as \(i \to \infty\). Upon integrating (3.4) over any interval \([t_i, t] \subset [t_i, T]\) we then find

\[\sup_{t_i < t < T} F(t) \leq F(t_i) + (C_2 + C_3 \sup_{t_i < t < T} F(t)) \int_{t_i}^\infty F(t) \, dt.\]
But by (3.5) we also have \( \int_{t_i}^{\infty} F(t) \, dt \to 0 \) as \( i \to \infty \). Hence, for sufficiently large \( i \in \mathbb{N} \) we can absorb the last term on the right on the left hand side of this inequality and let \( T \to \infty \) to find

\[
\sup_{t > t_i} F(t) \leq 2F(t_i) + 2C_2 \int_{t_i}^{\infty} F(t) \, dt \to 0 \quad \text{as} \quad i \to \infty,
\]

proving our claim. 

\[ \Box \]

**Proof of Theorem 1.2.** In view of (1.10) and Lemma 2.4 for suitable \( t_i \to \infty \) we have \( u_i = u(t_i) \to u_\infty \) weakly in \( H^1(M, g_b) \) and strongly in \( L^2(M, g_b) \), as well as \( \alpha_i = \alpha(t_i) \to \alpha_\infty \) (\( i \to \infty \)). Moreover, in view of Lemmas 2.3 and 3.3 we then also have convergence \( e^{2u_i} \to e^{2u_\infty} \) in \( L^p(M, g_b) \) for any \( p < \infty \), as well as \( e^{2u_i} u_i(t_i) \to 0 \) in \( L^2(M, g_b) \). Thus, passing to the limit \( i \to \infty \) in the equation

\[
e^{2u_i} u_i - \Delta_{g_b} u = \alpha f e^{2u_i}
\]
equivalent to (1.9) at \( t = t_i \), we find the identity

\[
- \Delta_{g_b} u_\infty = \alpha_\infty f e^{2u_\infty} \quad \text{on} \quad M.
\]

In fact, since at \( t = t_i \) by Lemmas 2.5 and 3.3 with \( L^2 = L^2(M, g_b) \), etc., we can estimate

\[
\| \Delta_{g_b} (u_i - u_\infty) \|_{L^2} \leq \| e^{u_i} \|_{L^\infty} F(t_i)^{1/2} + \| \alpha_i f e^{2u_i} - \alpha_\infty f e^{2u_\infty} \|_{L^2}
\]

\[
\leq \| e^{u_i} \|_{L^\infty} F(t_i)^{1/2} + \| \alpha_i - \alpha_\infty \|_{L^\infty} \| f e^{2u_i} \|_{L^\infty}
\]

\[
+ \| \alpha_\infty f \|_{L^\infty} \| e^{2u_i} - e^{2u_\infty} \|_{L^2} \to 0 \quad (i \to \infty),
\]

we even have strong convergence \( u_i \to u_\infty \) in \( H^2(M, g_b) \) and uniformly.

Note that \( \alpha_\infty \neq 0 \); else \( u_\infty \) would be constant, and from (1.3), (1.4) we obtain the contradiction

\[
0 = \lim_{i \to \infty} \int_M f e^{2u_i} \, d\mu_{g_b} = \int_M f e^{2u_\infty} \, d\mu_{g_b} = e^{2u_\infty} \int_M f \, d\mu_{g_b} < 0.
\]

In fact, \( \alpha_\infty > 0 \). Otherwise, if we assume that \( \alpha_\infty < 0 \), using (1.3) and computing

\[
0 \leq 2 \int_M |\nabla g_b u_\infty|^2 e^{-2u_\infty} \, d\mu_{g_b}
\]

\[
= \int_M \Delta_{g_b} u_\infty e^{-2u_\infty} \, d\mu_{g_b} = -\alpha_\infty \int_M f \, d\mu_{g_b} < 0
\]

we again find a contradiction. We thus may let \( c_\infty = \frac{1}{2} \log \alpha_\infty \in \mathbb{R} \). Setting \( \hat{u}_\infty = u_\infty + c_\infty \) then the metric \( \hat{g}_\infty = e^{2u_\infty} g_b \) has curvature \( K_{\hat{g}_\infty} = f \).

This completes the proof of Theorem 1.2. 

\[ \Box \]

In general we cannot say whether we have uniform convergence \( u(t) \to u_\infty \) as \( t \to \infty \). However, we have the following result.

**Theorem 3.2.** Suppose that \( u_\infty \) is a strict relative minimizer of \( E \) in \( C^* \) in the sense that with a constant \( c_0 > 0 \) there holds

\[
d^2 L_{u_\infty}(h, h) = \int_M (|\nabla g_b h|^2 - 2\alpha_\infty f h^2 e^{2u_\infty} ) \, d\mu_{g_b} \geq 2c_0 \| h \|_{H^1}^2
\]

for all \( h \in T_{u_\infty} C^* \), where for \( u \in C^* \) we let

\[ T_u C^* = \{ h \in H^1(M, g_b); \int_M f h^2 \, d\mu_{g_b} = 0 = \int_M h e^{2u} \, d\mu_{g_b} \}; \]

\[ T_0 C^* = \{ h \in H^1(M, g_b); \int_M h^2 \, d\mu_{g_b} = 0 \}. \]
and where for \( u = u(t) \) or \( u = u_\infty \) with \( \alpha = \alpha(t) \) or \( \alpha = \alpha_\infty \) we let

\[
L_u(v) = E(v) - \frac{\alpha}{2} \int_M f e^{2v} \, d\mu_{g_0}.
\]

be the Lagrange functional associated with \( u \). Then \( u(t) \to u_\infty \), \( \alpha(t) \to \alpha_\infty \) exponentially fast as \( t \to \infty \); that is, with constants \( C > 0 \) there holds

\[
F(t) = \|\alpha - K\|_{L^2(g)}^2 \leq Ce^{-2\alpha t},
\]

and hence

\[
|\alpha(t) - \alpha_\infty| + \|u(t) - u_\infty\|_{H^2(M, g_0)} \leq Ce^{-\alpha_\infty t}.
\]

Proof. First observe that by (3.2) and a variant of (3.3) on account of Lemma 3.1 with error \( o(1) \) to \( t \to \infty \) there holds

\[
\frac{1}{2} \frac{dF}{dt} \leq -(1 + o(1)) \int_M |\nabla(K - \alpha f)|^2 g_0 d\mu_g + 2\alpha \int_M f(K - \alpha f)^2 d\mu_g + o(1) F
\]

\[
= -(1 + o(1)) d^2 L_u(u_t, u_t) + o(1) F,
\]

where

\[
d^2 L_u(u_t, u_t) = \int_M (|\nabla u_t|^2 g_0 - 2\alpha f u_t^2 e^{2u} ) d\mu_{g_0}.
\]

Moreover, by (1.7) and (1.11) we have \( u_t = \alpha f - K \in T_u C^* \) for any \( t > 0 \).

Suppose that for some \( 0 < \rho < 1 \) and some \( t > 0 \) we have

\[(3.8)|\alpha(t) - \alpha_\infty| + \|u(t) - u_\infty\|_{H^2(M, g_0)} \leq 2\rho.
\]

Then there exist constants \( \gamma, \delta \in \mathbb{R} \) such that \( u_t + \gamma + \delta f \in T_u C^* \), and with \( g_\infty = e^{2u_\infty} g_0 \) the equations

\[
0 = \int_M (u_t + \gamma + \delta f) d\mu_{g_\infty} = \int_M u_t (e^{2(u_\infty - u)} - 1) d\mu_g + \gamma,
\]

\[
0 = \int_M (u_t + \gamma + \delta f) f d\mu_{g_\infty} = \int_M u_t f (e^{2(u_\infty - u)} - 1) d\mu_g + \delta \int_M f^2 d\mu_{g_\infty},
\]

respectively, give the bounds

\[
|\gamma| + |\delta| \leq C \|u(t) - u_\infty\|_{L^\infty} F^{1/2}(t) \leq C \rho F^{1/2}(t).
\]

Here we also use equations (1.7), (1.11), as well as the identities

\[
\int_M d\mu_{g_\infty} = 1, \quad \int_M f d\mu_{g_\infty} = 0,
\]

and Lemma 2.3. In consequence, setting \( h_0 = u_t + \gamma + \delta f \) for brevity, we have

\[
d^2 L_u(u_t, u_t) = \int_M (|\nabla u_t|^2 g_0 - 2\alpha f u_t^2 e^{2u} ) d\mu_{g_0}
\]

\[
= d^2 L_{u_{\infty}}(h_0, h_0) + I + II \geq 2\alpha_0 \|h_0\|_{H^1}^2 + I + II
\]

with error terms

\[
I = \int_M (|\nabla u_t|^2 g_0 - |\nabla h_0|^2 g_0) d\mu_{g_0} = -\delta \int_M \nabla f \cdot \nabla (2u_t + \delta f) d\mu_{g_0}
\]

\[
= 2\delta \int_M u_t \Delta g_0 f d\mu_{g_0} - \delta^2 \int_M |\nabla f|^2 g_0 d\mu_{g_0} = O(\rho F),
\]
where \( a \cdot b = (a, b)_\mu \), and

\[
II = 2 \int_M \left( \alpha_f h_0^2 e^{2u} - \alpha f u_t^2 e^{2u} \right) d\mu_g
\]

\[
= 2\alpha \int_M f \left( h_0^2 e^{2u} - u_t^2 e^{2u} \right) d\mu_g + O(\rho F)
\]

\[
= 2\alpha \int_M f \left( \left( h_0^2 - u_t^2 \right) + u_t^2 (1 - e^{2(u - u_\infty)}) \right) d\mu_g + O(\rho F) = O(\rho F).
\]

Moreover, similar computations give

\[
\|h_0\|_{L^2}^2 = \|u_t\|_{L^2}^2 + O(\rho F), \quad \|\nabla h_0\|_{L^2}^2 = \|\nabla u_t\|_{L^2}^2 - I = \|\nabla u_t\|_{L^2}^2 + O(\rho F).
\]

Hence for sufficiently small \( \rho > 0 \) and all sufficiently large \( t > 0 \) satisfying (3.8) we have

\[
(3.9) \quad \frac{1}{2} \frac{dF}{dt} \leq -(2c_0 + o(1)) \|u_t\|_{H^1}^2 + O(\rho F) + o(1) F \leq -c_0 F.
\]

Having fixed such \( \rho > 0 \), now assume that for some \( t_0 > 0 \) there holds

\[
(3.10) \quad |\alpha(t_0) - \alpha_\infty| + \|u(t_0) - u_\infty\|_{H^2(M, g_0)} \leq \rho.
\]

Then, if \( t_0 > 0 \) is sufficiently large, from (3.9) we find

\[
(3.11) \quad F(t) \leq F(t_0) e^{-2c_0(t-t_0)}
\]

for all \( t > t_0 \), as long as there holds (3.8). We claim that if \( t_0 > 0 \) is sufficiently large, the bound (3.8) and hence also (3.11) will, in fact, hold true for all \( t > t_0 \).

Indeed, from (1.8) and (3.1) we have the equation

\[
(3.12) \quad \alpha_\mu \int_M f^2 d\mu_g = \int_M f(K_t + 2K u_t) d\mu_g - 2\alpha \int_M f^2 u_t d\mu_g
\]

\[
\quad \quad = -\int_M f \Delta_g u_t d\mu_g - 2\alpha \int_M f^2 u_t d\mu_g.
\]

Integrating by parts, we have

\[
\left| \int_M f \Delta_g u_t d\mu_g \right| = \left| \int_M \Delta_g f u_t d\mu_g \right| \leq C \|f\|_{C^2} \|u_t\|_{L^2(M, g)} \leq CF(t)^{1/2}.
\]

Moreover, by Hölder’s inequality we can bound

\[
\left| \alpha \int_M f^2 u_t d\mu_g \right| \leq C \|u_t\|_{L^2(M, g)} \leq CF(t)^{1/2}.
\]

Thus, from (3.11) we have

\[
\left| \alpha(t) - \alpha(t_0) \right| \leq CF(t_0)^{1/2} \leq CF(t_0)^{1/2} e^{-c_0(t-t_0)}.
\]

and for any \( t > t_0 \) we obtain

\[
(3.13) \quad \|u(t) - u(t_0)\|_{L^2(M, g_0)} \leq \int_{t_0}^t \|u(t_0)\|_{L^2(M, g_0)} ds \leq CF(t_0)^{1/2}.
\]

as long as there holds (3.8). Similarly, also using Lemma 2.5, with a constant \( C = C(E(u_0)) \) we can bound
Again, (1.3) and (1.4) imply that $\beta$ is the unique solution of equation (1.2). It follows that there exists a subsequence $\Lambda_i$ such that, as in the proof of Theorem 1.2, by (1.10) as well as Lemmas 2.4 and 2.5 there holds for all sufficiently large $t > t_0$, as claimed.

Finally, passing to the limit $t = t_i \to \infty$ in (3.11) we see that we have

$$|\alpha| + \|u_\infty - u(t_0)\|_{H^2(M,g_b)} \leq CF(t_0)^{1/2}$$

for all sufficiently large $t_0 > 0$. Renaming $t_0$ as $t$, and choosing $t_0 > 0$ such that (3.11) holds for all $t > t_0$, we then obtain the claim.

Moreover, we have uniform convergence of the flow (1.6), (1.7) whenever the solution to (1.2) is unique.

**Theorem 3.3.** Suppose that (1.2) has a unique solution. Then $u(t) \to u_\infty$ in $H^2(M,g_b)$ as $t \to \infty$.

**Proof.** Suppose by contradiction that there exists $\rho > 0$ and a sequence $t_i \to \infty$ such that

$$\|u(t_i) - u_\infty\|_{H^2(M,g_b)} \geq \rho \quad \text{for all } i \in \mathbb{N}.$$

Then, as in the proof of Theorem 1.2 by (1.10) as well as Lemmas 2.4 and 2.5 there exists a subsequence $\Lambda_i \subset \mathbb{N}$ and a function $v_\infty$ such that $v_i = u(t_i) \to v_\infty$ weakly in $H^1(M,g_b)$ with $e^{2v_i} \to e^{2v_\infty}$ in $L^p(M,g_b)$ for any $p < \infty$ as $i \to \infty$, $i \in \Lambda$, and such that, in addition $\beta_i = \alpha(t_i) \to \beta_\infty$. Still following the proof of Theorem 1.2 with the help of Lemma 3.1 we then conclude strong convergence $v_i \to v_\infty$ in $H^2(M,g_b)$, and $v_\infty \in C^\infty$ solves the equation

$$-\Delta_{g_b} v_\infty = \beta_\infty f e^{2v_\infty} \quad \text{on } M.$$

Again, (1.3) and (1.4) imply that $\beta_\infty > 0$ and, with $d_\infty = \frac{1}{2}\log \beta_\infty \in \mathbb{R}$, the function $\hat{v} = v_\infty + d_\infty$ solves (1.2).

But by assumption the function $\hat{u}$ constructed in the proof of Theorem 1.2 is the unique solution of equation (1.2). It follows that $\hat{v} = \hat{u} = u_\infty + c_\infty$, and $v_\infty = u_\infty + c_\infty - d_\infty$. But then from (1.12) we obtain

$$1 = \int_M e^{2v_\infty} \mu_{g_b} = e^{2(c_\infty - d_\infty)} \int_M e^{2u_\infty} \mu_{g_b} = e^{2(c_\infty - d_\infty)}.$$

Hence $c_\infty = d_\infty$; that is, $v_\infty = u_\infty$, and $v_i \to u_\infty$ in $H^2(M,g_b)$ contrary to our initial assumption.

Our next goal is to analyze the “shape” of the metrics $g(t)$ and to establish “bubbling” of the prescribed curvature flow analogous to [23] in a certain limit regime.

We first consider the static (time-independent) case.
4. “Bubble” analysis in the static case

4.1. Bounds for total curvature. Let \( f_0 \) be a smooth, non-constant function with \( \max_{p \in M} f_0(p) = 0 \), and for any \( \lambda \in \mathbb{R} \) let \( f_\lambda = f_0 + \lambda \) as in [10], [1], or [12]; also set \( \mathcal{C}_\lambda = \mathcal{C}_{f_\lambda}, \mathcal{C}_\lambda^* = \mathcal{C}_{f_\lambda}^* \).

Fix some sufficiently small \( \lambda_0 > 0 \) so that \( f_{\lambda_0} \) changes sign and satisfies (1.3). For any \( 0 < \lambda < \lambda_0 \) then by Theorem 1.1 there exists a solution \( \tilde{u}_\lambda = u_\lambda + c_\lambda \) of (1.2), where \( u_\lambda \) minimizes \( E \) in the set \( \mathcal{C}_\lambda^* \) and thus satisfies the equation

\[
\Delta u_\lambda = \alpha_\lambda f_\lambda e^{2u_\lambda}
\]

with a constant \( \alpha_\lambda > 0 \), and where \( c_\lambda = \frac{1}{2} \log \alpha_\lambda \). Moreover, setting \( \tilde{g}_\lambda = e^{2\alpha_\lambda} g_\lambda \) we have

\[
\text{vol}(M, \tilde{g}_\lambda) = \int_M e^{2(u_\lambda + c_\lambda)} d\mu_{g_\lambda} = e^{2c_\lambda} = \alpha_\lambda.
\]

Note that by Theorem 1.1 we must have

\[
\beta_\lambda := E(u_\lambda) = \min \{ E(u); u \in \mathcal{C}_\lambda^* \} \to \infty \quad \text{as} \ \lambda \downarrow 0;
\]

Indeed, if we assume \( \beta_\lambda \leq C_1 \) and express \( |f_0| = -f_0 = \lambda - f_\lambda \), condition (1.3) and the Gauss-Bonnet identity (1.4) together with (1.12) and the bound (2.4) give

\[
0 < \left( \int_M |f_0| d\mu_{g_\lambda} \right)^2 \leq \int_M |f_0| e^{-2\alpha_\lambda} d\mu_{g_\lambda} \cdot \int_M |f_0| e^{2\alpha_\lambda} d\mu_{g_\lambda} \leq C \|f_0\|_{L^\infty} \int_M (\lambda - f_\lambda) e^{2\alpha_\lambda} d\mu_{g_\lambda} = C \lambda \|f_0\|_{L^\infty},
\]

with a constant \( C > 0 \) depending only on \( C_1 \), which is only possible if \( \lambda > \lambda_1 \) for some \( \lambda_1 > 0 \).

On the other hand, as shown by Galimberti [12] with the help of the method introduced in [1] for surfaces of genus larger than one, for suitable \( \lambda \downarrow 0 \) the total curvature of the metrics \( \tilde{g}_\lambda = e^{2\alpha_\lambda} g_\lambda \) is uniformly bounded. The crucial ingredient in the derivation of this bound is the following monotonicity property established by Galimberti [12], Proposition 3.7 and Corollary 3.8.

**Lemma 4.1.** The function \( \lambda \mapsto \beta_\lambda \) is non-increasing in \( \lambda \) for \( 0 < \lambda < \lambda_0 \), and for every such \( \lambda \) we have the bound

\[
\limsup_{\mu \downarrow \lambda} \frac{\beta_\lambda - \beta_\mu}{\mu - \lambda} \geq \frac{\alpha_\lambda}{2}.
\]

The argument by Galimberti [12] is rather long and technical. For our later convenience we therefore include the following short proof.

**Proof.** Fix \( 0 < \lambda < \lambda_0 \), and let \( u_\lambda \in \mathcal{C}_\lambda^* \) be a minimizer of \( E \) as above. Then for small \( \delta \in \mathbb{R} \) we have

\[
\int_M f_\lambda e^{2(u_\lambda + \delta f_\lambda)} d\mu_{g_\lambda} = 2\delta \int_M f_\lambda^2 e^{2u_\lambda} d\mu_{g_\lambda} + O(\delta^2),
\]

while

\[
\int_M e^{2(u_\lambda + \delta f_\lambda)} d\mu_{g_\lambda} = 1 + 2\delta \int_M f_\lambda e^{2u_\lambda} d\mu_{g_\lambda} + O(\delta^2) = 1 + O(\delta^2).
\]

Thus, if \( 0 < |\delta| \ll 1 \) is sufficiently small it follows that

\[
u_\lambda + \delta f_\lambda \in \mathcal{C}_\mu
\]
with
\[ (4.4) \quad \mu = \lambda - 2\delta \int_M f_\lambda^2 e^{2u_\lambda} \, d\mu_{gb} + O(\delta^2). \]
In particular, \( \mu > \lambda \) for \( \delta < 0 \) sufficiently close to zero, and \( \delta = O(\mu - \lambda) \). On the other hand, we have
\[ E(u_\lambda + \delta f_\lambda) = E(u_\lambda) + \delta \int_M \nabla u_\lambda \cdot \nabla f_\lambda \, d\mu_{gb} + O(\delta^2), \]
where
\[ \int_M \nabla u_\lambda \cdot \nabla f_\lambda \, d\mu_{gb} = \int_M (-\Delta_{gb} u_\lambda f_\lambda) \, d\mu_{gb} = \alpha \int_M f_\lambda^2 e^{2u_\lambda} \, d\mu_{gb} \]
in view of (4.3), and by (4.4) there holds
\[ \beta_\mu \leq E(u_\lambda + \delta f_\lambda) \leq E(u_\lambda) + \delta \alpha \int_M f_\lambda^2 e^{2u_\lambda} \, d\mu_{gb} + O(\delta^2) \]
\[ = \beta_\lambda - \frac{\alpha \lambda}{2} (\mu - \lambda) + O((\mu - \lambda)^2) < \beta_\lambda \]
for \( \delta < 0 \) sufficiently close to zero. Hence, the map \( \lambda \mapsto \beta_\lambda \) is non-increasing, and
\[ \limsup_{\mu \downarrow \lambda} \frac{\beta_\lambda - \beta_\mu}{\mu - \lambda} \geq \frac{\alpha \lambda}{2}, \]
as claimed.

Moreover, using the same comparison function as in [1], Lemma 3.1, also used by Galimberti [12], we find the following bound on \( \beta_\lambda \).

**Lemma 4.2.** There holds
\[ \limsup_{\lambda \downarrow 0} \frac{\beta_\lambda}{\log(1/\lambda)} \leq 4\pi. \]

Galimberti [12], Proposition 3.3, obtains a similar bound with an unspecified constant instead of \( 4\pi \).

**Proof.** Let \( p_0 \in M \) be such that \( f_0(p_0) = 0 \). We may assume that we have local Euclidean coordinates \( x \) near \( p_0 = 0 \). Letting \( A = \frac{1}{\tau} \text{Hess}_f(p_0) \), for a suitable constant \( L > 0 \) we have
\[ f_0(x) = \langle Ax, x \rangle + O(|x|^3) \geq -\lambda/2 \text{ on } B_{\sqrt{\tau}/L}(0), \]
and \( f_\lambda \geq \lambda/2 \) on \( B_{\sqrt{\tau}/L}(0) \). As in [1] we then set \( w_\lambda(x) = z_\lambda(Lx/\sqrt{\lambda}) \), where \( z_\lambda \in H_0^1(B_1(0)) \) is given by \( z_\lambda(x) = \log(1/|x|) \) for \( \lambda \leq |x| \leq 1 \) and \( z_\lambda(x) = \log(1/\lambda) \) for \( |x| \leq \lambda \), satisfying
\[ \|\nabla w_\lambda\|_{L^2}^2 = \|\nabla z_\lambda\|_{L^2}^2 = 2\pi \log(1/\lambda). \]
Extending \( w_\lambda(x) = 0 \) outside \( B_{\sqrt{\tau}/L}(0) \), for sufficiently small \( \lambda > 0 \) and any \( s > 0 \) we obtain
\[ \int_M f_\lambda e^{2sw_\lambda} \, d\mu_{gb} = \int_M f_\lambda \, d\mu_{gb} + \int_{B_{\sqrt{\tau}/L}(0)} f_\lambda (e^{2sw_\lambda} - 1) \, dx \]
\[ = \int_M f_0 \, d\mu_{gb} + \lambda + \int_{B_{\sqrt{\tau}/L}(0)} f_\lambda (e^{2sw_\lambda} - 1) \, dx. \]
Note that after substituting \( y = Lx / \sqrt{\lambda} \) for \( s > 1 \) we have
\[
\lambda \int_{B_{\sqrt{\lambda}/L}(0)} e^{2sw_\lambda} \, dx = \frac{\lambda^2}{L^2} \int_{B_1(0)} e^{2sz_\lambda} \, dy = \frac{\pi \lambda^{4-2s}}{L^2} + \frac{2\pi \lambda^2}{L^2} \int_{\lambda}^{1} r^{1-2s} \, dr
\]
\[
= \frac{\pi \lambda^{4-2s}}{L^2} + \frac{\pi \lambda^{4-2s}}{(s-1)L^2} - \frac{\pi \lambda^2}{(s-1)L^2}.
\]
Since we have \( \lambda/2 \leq f_\lambda \leq \lambda \) on \( B_{\sqrt{\lambda}/L}(0) \), for \( 3/2 \leq s \leq 3 \) we can estimate
\[
\frac{3\pi}{4L^2} \lambda^{4-2s} - \frac{3\pi}{L^2} \lambda^2 \leq \int_{B_{\sqrt{\lambda}/L}(0)} f_\lambda(e^{2sw_\lambda} - 1) d\mu_{\bar{g}_0} \leq \frac{3\pi}{L^2} \lambda^{4-2s} - \frac{3\pi}{4L^2} \lambda^2.
\]
Hence for \( s = 2 + O(1/\log(1/\lambda)) \) we can achieve that \( sw_\lambda \in C_\lambda \) with
\[
\|\nabla(sw_\lambda)\|_{L^2}^2 = s^2\|\nabla w_\lambda\|_{L^2}^2 = 8\pi \log(1/\lambda) + O(1).
\]
Thus, for any \( K > 4\pi \) and sufficiently small \( \lambda > 0 \) there results
\[
\beta_\lambda \leq K \log(1/\lambda),
\]
as desired. \( \square \)

Applying the monotonicity trick from [19, 20] as in [1] or [12], we observe that the monotone function \( \beta_\lambda \) is almost everywhere differentiable and then use the bounds from Lemmas 4.1, 4.2 to obtain that
\[
\liminf_{\lambda \downarrow 0} (\lambda \alpha_\lambda) \leq 2 \liminf_{\lambda \downarrow 0} \left( \lambda \frac{|d\beta_\lambda|}{d\lambda} \right) \leq 8\pi.
\]
Indeed, if we assume that for some \( 0 < \lambda_1 < \lambda_0 \) and some \( c_0 > 4\pi \) for all \( 0 < \lambda < \lambda_1 \) the absolutely continuous part of the differential of \( \beta_\lambda \) satisfies
\[
|\beta'_\lambda| = \left| \frac{d\beta_\lambda}{d\lambda} \right| \geq \frac{c_0}{\lambda},
\]
then for \( K = 2\pi + c_0/2 > 4\pi \) and any sufficiently small \( 0 < \lambda < \lambda_1 \) we obtain
\[
\beta_\lambda - \beta_{\lambda_1} \geq \int_{\lambda}^{\lambda_1} |\beta'_s| \, ds \geq c_0 \int_{\lambda}^{\lambda_1} \frac{ds}{s} \geq c_0 \log(1/\lambda) + C > K \log(1/\lambda),
\]
contradicting the bound in Lemma 4.2.

Estimating
\[
|K_{\bar{g}_{\lambda}}| = |f_\lambda| \leq -f_0 + \lambda = -f_\lambda + 2\lambda,
\]
from (4.5) and (4.2) together with (1.4) we then conclude the bound
\[
\liminf_{\lambda \downarrow 0} \int_M |K_{\bar{g}_{\lambda}}| \, d\mu_{\bar{g}_{\lambda}} \leq 2 \liminf_{\lambda \downarrow 0} (\lambda \alpha_\lambda) \leq 16\pi
\]
for the total curvature of the metrics \( \bar{g}_{\lambda} \). For the normalized metrics \( g_{\lambda} = e^{2u_\lambda} g_b \) we then have \( K_{\bar{g}_{\lambda}} = \alpha_\lambda K_{\bar{g}_{\lambda}} \) and \( \int_M |K_{\bar{g}_{\lambda}}| \, d\mu_{\bar{g}_{\lambda}} = \int_M |K_{\bar{g}_{\lambda}}| \, d\mu_{\bar{g}_{\lambda}}. \)
4.2. Concentration of curvature. Motivated by (4.7) in the following for a sequence \( \lambda_k \downarrow 0 \) we consider functions \( v_k \in C^*_{\alpha_k} \) with corresponding metrics \( g_k = e^{2v_k}g_b \) such that
\[
\Delta g_k v_k = K_{g_k} e^{2v_k} = \alpha_k f_{\lambda_k} e^{2v_k} + h_k e^{2v_k}
\]
with \( \alpha_k \) satisfying \( \limsup_{k \to \infty} (\lambda_k \alpha_k) \leq 8\pi \), and with functions \( h_k \) on \( M \) such that \( \|h_k e^{2v_k}\|_{L^2(M,g_k)} = \varepsilon_k \to 0 \) as \( k \to \infty \). In particular, for suitable \( \lambda_k \downarrow 0 \) in view of (4.5) we may choose \( v_k = u_{\lambda_k} \in C^*_{\lambda_k} \), satisfying (4.8) with \( h_k = 0 \), \( k \in \mathbb{N} \). However, by allowing the “error term” \( h_k \) we later will be able to apply the results below also in the flow context, where \( v_k = u(t_k) \) for a solution \( u = u(t) \) to (1.6), (1.7) and \( h_k = u(t_k) \) for a sequence of times \( t_k \to \infty \).

Set \( s^\pm = \pm \max\{\pm s, 0\} \) for any \( s \in \mathbb{R} \). Note that similar to (4.9), upon writing \( |K_{g_k}| = -K_{g_k} + 2K_{g_k}^+ \) and estimating \( K_{g_k}^+ \leq \alpha_k \lambda_k + |h_k| \), from the Gauss-Bonnet identity (or by integrating (4.8)) we obtain the bound
\[
\limsup_{k \to \infty} \int_M |K_{g_k}| d\mu_{g_k} = 2 \limsup_{k \to \infty} \int_M K_{g_k}^+ e^{2v_k} d\mu_{g_k} \leq 2 \limsup_{k \to \infty} (\alpha_k \lambda_k + \|h_k e^{2v_k}\|_{L^2(M,g_k)}) \leq 16\pi
\]
similar to (4.7) for the total curvature of the metrics \( g_k, k \in \mathbb{N} \).

**Lemma 4.3.** Given \( (v_k) \) as above we have \( \alpha_k \to \infty \) as \( k \to \infty \). Moreover, there is a sequence of radii \( R_k \to 0 \) such that with error \( o(1) \to 0 \) as \( k \to \infty \) there holds
\[
\sup_{p_0 \in M} \int_{B_R(p_0)} K_{g_k}^+ d\mu_{g_k} = \pi/2 + o(1).
\]

**Proof.** Suppose by contradiction that there exists a sequence \( \Lambda \subset \mathbb{N} \), and \( R > 0 \) such that for all \( k \in \Lambda \) there holds
\[
\sup_{p_0 \in M} \int_{B_R(p_0)} K_{g_k}^+ d\mu_{g_k} < \pi.
\]
In particular, by (4.9) condition (4.11) will be satisfied if \( \liminf_{k \to \infty} \alpha_k < \infty \). With no loss of generality we may assume that \( \Lambda = \mathbb{N} \) and that \( R > 0 \) is so small that we can introduce Euclidean coordinates on \( B_R(p_0; g_0) \) for any \( p_0 \in M \).

i) We claim that the functions \( v_k \) are uniformly bounded on \( M \) from above. Fix a point \( p_0 \in M \). In Euclidean coordinates around \( p_0 = 0 \) we then obtain the equation
\[
-\Delta v_k = K_{g_k} e^{2v_k} \text{ on } B = B_R(0).
\]
Split \( v_k = v_k^{(0)} + v_k^{(+)} + v_k^{(-)} \), where \( \Delta v_k^{(0)} = 0 \) in \( B \) with \( v_k^{(0)} = v_k \) on \( \partial B \), and where \( v_k^{(\pm)} \in H_0^1(B) \) solve
\[
-\Delta v_k^{(\pm)} = K_{g_k}^\pm e^{2v_k} \text{ on } B.
\]
Then \( v_k^{(\pm)} \geq 0 \) by the maximum principle. Moreover, in view of the uniform \( L^1 \)-bound (4.9) we also have uniform bounds
\[
\|v_k^{(\pm)}\|_{W^{1,p}(B)} \leq C \text{ for any } 1 \leq p < 2.
\]
Hence a subsequence \( (v_k^{(\pm)}) \) converges weakly in \( W^{1,3/2}(B) \) and pointwise almost everywhere. Finally, from (4.11) and [3], Theorem 1, we have the uniform bound
\[
\|e^{v_k^{(+)}}\|_{L^p(B)} \leq C \text{ for any } 1 \leq p < 4.
\]
Likewise, if we choose \( \gamma = 1/20 > 0 \) so that
\[
\gamma \int_M |K_{g_k}| \, d\mu_{g_k} \leq \pi
\]
for all sufficiently large \( k \in \mathbb{N} \), from \[3\], Theorem 1, we find
\[
(4.13) \quad \|e^{-\gamma v_k^{(-)}}\|_{L^p(B)} \leq C \text{ for any } 1 \leq p < 4.
\]

Thus, by Jensen’s inequality and in view of \( v_k^{(0)} \leq v_k^{(-)} \), on any disc \( D \subset B \) the average of \( \gamma v_k^{(0)} \) can be bounded
\[
\exp\left( \int_D \gamma v_k^{(0)} \, dx \right) \leq \int_D e^{\gamma v_k^{(0)}} \, dx \leq C \left( \int_B e^{2\gamma v_k} \, dx \right)^{1/2} \left( \int_B e^{-2\gamma v_k^{(-)}} \, dx \right)^{1/2} \leq C \left( \int_M e^{2v_k} \, dx \right)^{\gamma/2} = C,
\]
where we used Hölder’s inequality in the second and in the final estimate.

By the mean value property of harmonic functions there results a uniform bound \( v_k^{(0)} \leq C_1 \) on \( B_{2R/3}(0) \) for all \( k \in \mathbb{N} \). Harnack’s inequality, applied to the functions \( C_1 - v_k^{(0)} \geq 0, k \in \mathbb{N} \), then shows that either for a subsequence we have \( |v_k^{(0)}| \leq C \) on \( B_{R/2}(0) \) for all \( k \in \mathbb{N} \), or \( v_k^{(0)} \to -\infty \) uniformly on \( B_{R/2}(0) \) as \( k \to \infty \).

Covering \( M \) with finitely many balls \( B_{R/2}(x_i), 1 \leq i \leq I, \) we note that for each \( B_i = B_R(x_i) \) we have
\[
\int_{B_i} K_{g_k}^+ \, d\mu_{g_k} \leq \pi, \quad 1 \leq i \leq I,
\]
and bounding \( v_k \leq v_k^{(+)} + v_k^{(0)} \leq v_k^{(+)} + C \) on each ball, from \[4.12\] we conclude
\[
\|e^{v_k}\|_{L^p(M,g_k)} \leq C \text{ for any } 1 \leq p < 4.
\]

Recalling the equation
\[
-\Delta v_k = K_{g_k} e^{2v_k} = \alpha_k f_{\lambda_k} e^{2v_k} + h_k e^{2v_k}
\]
with \( \alpha_k f_{\lambda_k} \leq \alpha_k \lambda_k \leq 8\pi + o(1) \) up to an error \( o(1) \to 0 \), and recalling that by assumption we have \( \|h_k e^{2v_k}\|_{L^2} \to 0 \) as \( k \to \infty \), we then obtain a uniform bound
\[
v_k^{(+)} \leq C\|v_k^{(+)}\|_{W^{2,3/2}} \leq C \text{ on } B_R(x_i), \text{ uniformly in } 1 \leq i \leq I, \text{ and hence } v_k \leq C \text{ on } M, \text{ uniformly in } k \in \mathbb{N}.
\]

In addition, we now conclude the uniform bound \( |v_k^{(0)}| \leq C \) on every ball \( B_{R/2}(x_i), 1 \leq i \leq I, \) for some \( C \) independent of \( i \) and \( k \in \mathbb{N} \). Indeed, if we suppose that \( v_k^{(0)} \to -\infty \) and hence \( v_k \leq v_k^{(+)} + v_k^{(0)} \leq C + v_k^{(0)} \to -\infty \) uniformly as \( k \to \infty \) on some ball \( B_{R/2}(x_i) \), by considering the decompositions of \( v_k \) in the overlap regions of adjacent balls, we must have \( v_k^{(0)} \to -\infty \) uniformly as \( k \to \infty \) on every \( B_{R/2}(x_i), 1 \leq i \leq I \). But then \( v_k \to -\infty \) uniformly on \( M \) as \( k \to \infty \), contradicting \[1.12\]. Thus, \( |v_k^{(0)}| \leq C \) on every ball \( B_{R/2}(x_i) \), and by harmonicity of \( v_k^{(0)} \) a subsequence \( (v_k^{(0)}) \) smoothly converges locally on every ball \( B_{R/2}(x_i) \), ensuring that \( v_k \to v_{\infty} \) weakly in \( W^{1,3/2}(M) \) and pointwise almost everywhere.

\( ii \) We can now show that \( \alpha_k \to \infty \) as \( k \to \infty \). Indeed, suppose by contradiction that we have a uniform bound \( \alpha_k \leq C < \infty \). Then by \( i \) with a constant \( C > 0 \) independent of \( k \) we have the uniform bound \( v_k \leq C \) on \( M \), and together with the bound \( se^s \geq -1 \) for \( s \leq 0 \) we find that \( \alpha_k f_{\lambda_k} e^{v_k} \leq C \), uniformly on \( M \).
Moreover, we have \(|v_k|_{L^2} \leq C\|v_k\|_{W^{1,3/2}} \leq C\). But then upon multiplying \((4.8)\) with \(v_k\) we obtain the bound
\[
\beta_{\lambda_k} \leq \int_M |\nabla v_k|^2 \, d\mu_{\gamma_k} \leq \int_M \alpha_k f_{\lambda_k} e^{2u_k} v_k \, d\mu_{\gamma_k} + \int_M h_k e^{2u_k} v_k \, d\mu_{\gamma_k} \\
\leq C + C\|h_k e^{2u_k}\|_{L^2} \|v_k\|_{L^2} \leq C,
\]
contradicting \((4.3)\).

iii) With ii) now also the second claim follows. Assuming \((4.11)\), recall that by part i) of the proof a subsequence \(v_k \rightarrow v_\infty\) weakly in \(W^{1,3/2}(\Omega)\) and pointwise almost everywhere. Fatou’s lemma then gives
\[
\liminf_{k \rightarrow \infty} \int_M |f_{\lambda_k} e^{2u_k} \, d\mu_{\gamma_k} \geq \int_M |f_0| e^{2u_\infty} \, d\mu_{\gamma_k} > 0.
\]
But recalling that \(\alpha_k \rightarrow \infty\) as \(k \rightarrow \infty\), and estimating
\[
\int_M \alpha_k f_{\lambda_k} e^{2u_k} \, d\mu_{\gamma_k} \leq \int_M |K_{\gamma_k}| \, d\mu_{\gamma_k} + \|h_k e^{2u_k}\|_{L^2} \leq 16\pi + o(1)
\]
with error \(o(1) \rightarrow 0\) as \(k \rightarrow \infty\) we then arrive at a contradiction. The proof is complete.

In particular, by Lemma 4.3 and 4.9 with error \(o(1) \rightarrow 0\) as \(k \rightarrow \infty\) there holds
\[(4.14)\quad \pi/2 - o(1) \leq \alpha_k \lambda_k \leq 8\pi + o(1)\] for all \(k \in \mathbb{N} \).

4.3. Blow-up analysis. In this section we partially complete Galimberti’s analysis of the shape of the metrics \(g_k\) in the time-independent case and extend his result to the more general case above. Like Galimberti’s work, our analysis follows the outline of our previous joint work with Borer [1].

**Theorem 4.4.** Let \(f_0 \leq 0\) be a smooth, non-constant function with \(\max f_0 = 0\) having only non-degenerate maxima \(p_0\) where \(f_0(p_0) = 0\). Then for any \((v_k)\) as above for suitable \(i_0 \in \mathbb{N}\), \(r_k^{(i)} \downarrow 0\), \(p_k^{(i)} \rightarrow p_\infty^{(i)} \in M\) with \(f_0(p_\infty^{(i)}) = 0\), \(1 \leq i \leq i_0\), for a subsequence \(k \rightarrow \infty\) the following holds.

i) We have \(v_k \rightarrow -\infty\) locally uniformly on \(M_\infty = M \setminus \{p_\infty^{(i)}; \ 1 \leq i \leq i_0\}\).

ii) For each \(1 \leq i \leq i_0\) there holds \(r_k^{(i)}/\sqrt{\lambda_k} \rightarrow 0\), and in local Euclidean coordinates \(x\) around \(p_k^{(i)} = 0\) with constants \(c_k^{(i)} \rightarrow \infty\) we have
\[
w_k^{(i)}(x) := v_k(r_k^{(i)}x) - c_k^{(i)} \rightarrow w_\infty(x) = \log(\frac{2}{1 + |x|^2}),
\]
in \(H_{loc}^2\) on \(\mathbb{R}^2\), where \(w_\infty\) induces the standard spherical metric \(g_\infty = e^{2w_\infty}g_{\mathbb{R}^2}\) on \(\mathbb{R}^2\) of curvature \(K_{g_\infty} \equiv 1\), and \(1 \leq i_0 \leq 2\).

Thus we can rule out one of the possible blow-up limits in Galimberti’s [12] Theorem 1.1; moreover, the proof of Theorem 4.4 may be carried over to the setting of [1] to obtain an analogous improvement of the results on “bubbling” metrics of prescribed curvature on surfaces of genus \(> 1\) considered there. However, like Galimberti we are not able to decide whether the metrics \(\hat{g}_k = e^{2v_k}g_b = \alpha_k e^{2v_k}g_b\) on the torus converge to a limit metric on \(M_\infty\) or vanish as \(k \rightarrow \infty\).

**Proof.** By \((4.9)\) and Lemma 4.3 for a subsequence \(k \rightarrow \infty\) we have
\[
K^+_{\hat{g}_k} e^{2v_k} \, d\mu_{\hat{g}_k} \rightarrow K^+ + \sum_{i \in I} \gamma_i \delta_{p_\infty^{(i)}}
\]
weakly-* in the sense of measures, with a measure $K_+ \geq 0$ on $(M, g_b)$ having no atoms and with at most countably many atoms of weight $\gamma_i > 0$, $i \in I \subset \mathbb{N}$. Note that (4.10) gives the bound $\sum_i \gamma_i \leq 8\pi$. Hence after relabelling there is $i_0 \in \mathbb{N}$ such that $\gamma_i \geq \pi/2$ if only if $1 \leq i \leq i_0$.

Also note that for any $p$ with $f_0(p) < 0$ we have $\limsup_{k \to \infty} K_{g_k} \leq 0$ near $p$; thus, necessarily there holds $f_0(p^{(i)}) = 0$, $1 \leq i \leq i_0$.

i) Given any open set $\Omega \subset \bar{\Omega} \subset \mathbb{R}^3 := M \setminus \{p^{(i)}; 1 \leq i \leq i_0\}$ there exists a radius $R > 0$ such that for any $p_0 \in \Omega$ in Euclidean coordinates around $p_0 = 0$ we have

$$
\int_{B_R(0)} K_{g_k}^+ \, d\mu_{g_k} < \pi
$$

for sufficiently large $k \in \mathbb{N}$.

Clearly we may assume that $\Omega$ is connected and is so large that $\int_\Omega f_0 \, d\mu_{g_b} < 0$. Covering $\Omega$ with finitely many balls $B_{R/2}(p_i)$, $1 \leq i \leq I$, and splitting $v_k = v_k^{(0)} + v_k^{(+) + v_k^{(-)}$ on each $B = B_i = B_R(p_i)$ as in the proof of Lemma 4.3, with $\gamma = 1/20$ we then have $\|v_k^{(\pm)}\|_{W^{1,3/2}(B)} \leq C$ as well as the uniform bounds

$$
\|e^{v_k}\|_{L^p(B)} + \|e^{-\gamma v_k}\|_{L^p(B)} \leq C \quad \text{for any } 1 \leq p < 4,
$$

and a subsequence $(v_k^{(\pm)})$ converges weakly in $W^{1,3/2}(B)$. Moreover, again arguing as in the proof of Lemma 4.3 we have uniform bounds $v_k^\pm \leq C$, $v_k^{(0)} \leq C_1$ on $B_{2R/3}(p_i)$, and either for a subsequence we have $|v_k^{(0)}| \leq C$ on each $B_{R/2}(p_i)$ for all $k \in \mathbb{N}$, or there holds $v_k \to -\infty$ uniformly on $\Omega$ as $k \to \infty$. (Here we use that $\Omega$ by assumption is connected.)

Suppose that for a subsequence we have $|v_k^{(0)}| \leq C$ uniformly on every ball $B_{R/2}(p_i)$, $1 \leq i \leq I$. Since $v_k^{(0)}$ is harmonic, then a subsequence $(v_k^{(0)})$ converges locally smoothly on $B_{R/2}(p_i)$, and it follows that $v_k \to v_\infty$ weakly in $W^{1,3/2}(\Omega)$ and pointwise almost everywhere. By Fatou's lemma then

$$
\liminf_{k \to \infty} \int_\Omega |f_{\lambda_k}| e^{2v_k} \, d\mu_{g_b} \geq \int_\Omega |f_0| e^{2v_\infty} \, d\mu_{g_b} > 0,
$$

and similar to our argument in the proof of Lemma 4.3 from the fact that $\alpha_k \to \infty$ as $k \to \infty$, we then derive a contradiction by estimating

$$
\int M |f_{\lambda_k}| e^{2v_k} \, d\mu_{g_b} \leq \int_M |K_{g_k}| \, d\mu_{g_k} + \|h_k e^{2v_k}\|_{L^2} \leq 16\pi + o(1).
$$

Thus $v_k \to -\infty$ uniformly on $\Omega$ as $k \to \infty$, proving the first claim.

ii) Next, consider any point $p_0 = p^{(i)}_{0}$, $1 \leq i \leq i_0$. In order to be able to follow our reasoning in [11] as closely as possible, we split $v_k = w_k + z_k$, where

$$
-\Delta_{g_k} z_k = (h_k - \bar{h}_k) e^{2v_k}
$$

with $\int_M z_k \, d\mu_{g_b} = 0$ and with

$$
\bar{h}_k = \int_M h_k e^{2v_k} \, d\mu_{g_b} \quad \text{satisfying } |\bar{h}_k| \leq \varepsilon_k \to 0 \text{ as } k \to \infty.
$$

Since

$$
\| (h_k - \bar{h}_k) e^{2v_k} \|_{L^2} \leq 2\| h_k e^{2v_k} \|_{L^2} = 2\varepsilon_k \to 0 \quad \text{as } k \to \infty,
$$
from elliptic regularity theory we have
\[
\|z_k\|_{L^\infty} \leq C \|z_k\|_{H^2} \leq C \|\Delta g_k z_k\|_{L^2} \to 0 \text{ as } k \to \infty.
\]

For any \( R > 0 \) now there holds
\[
\sup_{B_R(p_k)} w_k \to \infty \text{ as } k \to \infty;
\]
otherwise we have
\[
\int_{B_R(p_k)} K^+_g e^{2\omega_k} d\mu_{g_k} \leq \alpha_k \lambda_k e^{2\|z_k\|_{L^\infty}} \int_{B_R(p_k)} e^{2w_k} d\mu_{g_k} + \varepsilon_k \leq CR^2 + \varepsilon_k < \pi/4
\]
for sufficiently small \( R > 0 \) and sufficiently large \( k \in \mathbb{N} \), contrary to our assumption about \( p_0 \).

Thus, and in view of part i) of this proof for sufficiently large \( k \in \mathbb{N} \) there exists \( p_k \to p_0 \) such that \( w_k \) attains its maximum on \( B_R(p_0) \) at \( p_k \). In local Euclidean coordinates \( x \) near \( p_0 = 0 \) then \( p_k = x_k, \Delta w_k(x_k) \leq 0 \). From the equation
\[
-\Delta w_k = \alpha_k f_{\lambda_k} e^{2\omega_k} + \bar{h}_k e^{2\nu_k}.
\]

it then follows that
\[
\alpha_k f_{\lambda_k}(x_k) + \bar{h}_k = \alpha_k f_0(x_k) + \lambda_k + \bar{h}_k \geq 0,
\]
and from (4.14) we conclude that
\[
-f_0(x_k) \leq \lambda_k \left(1 + (\alpha_k \lambda_k)^{-1} \bar{h}_k\right) \leq 2\lambda_k
\]
for sufficiently large \( k \in \mathbb{N} \). Since \( p_0 \) by assumption is non-degenerate, there exists a constant \( C_1 > 0 \) such that \(-f_0(x) > 2\lambda_k \) for \(|x|^2 \geq C_1 \lambda_k, |x| \leq R \). It follows that \(|x_k|^2 \leq C_1 \lambda_k \); moreover, the bound \( \gamma_i \geq \pi/2 \) and (4.16) give
\[
1 \leq C\alpha_k \lambda_k^2 e^{2\omega_k(x_k)}.
\]

We are then left with two cases. First consider the case when \( \alpha_k \lambda_k^2 e^{2\omega_k(x_k)} \to \infty \). Let \( r_k^2/\alpha_k \lambda_k e^{2\omega_k(x_k)} = 1 \) with \( r_k^2/\lambda_k \to 0 \) as \( k \to \infty \), and rescale
\[
\hat{w}_k(x) = w_k(x + r_k x) - w_k(x) \leq \hat{w}_k(0) = 0, \quad \hat{z}_k(x) = z_k(x + r_k x)
\]
on \( D_k = \{ x \mid |x_k + r_k x| < R \} \). Note that by (4.14) we have \(|w_k(x_k) + \log r_k| \leq C \); moreover, as \( k \to \infty \) the domains \( D_k \) exhaust \( \mathbb{R}^2 \).

The function \( \hat{w}_k \) satisfies the equation
\[
-\Delta \hat{w}_k = r_k^2 (\alpha_k f_{\lambda_k}(x_k + r_k x) + \bar{h}_k) e^{2(\hat{w}_k + w_k(x_k) + \hat{z}_k)} = \tilde{f}_k e^{2\hat{z}_k} e^{2\hat{w}_k} \text{ on } D_k,
\]
where
\[
\tilde{f}_k(x) = r_k^2 (\alpha_k f_{\lambda_k}(x_k + r_k x) + \bar{h}_k) e^{2\omega_k(x_k)}
\]
\[
= 1 + \lambda_k^{-1} f_0(x_k + r_k x) + (\alpha_k \lambda_k)^{-1} \bar{h}_k.
\]

Since \((\alpha_k \lambda_k)^{-1} \bar{h}_k \leq C \varepsilon_k \to 0 \) as \( k \to \infty \) on account of (4.14), and since in addition we have \(|x_k|^2 \leq C_1 \lambda_k \) and \( r_k^2/\lambda_k \to 0 \), a subsequence \( \lambda_k^{-1} f_0(x_k + r_k x) \to c_0 \) for some constant \(-1 \leq c_0 \leq 0 \) and \( \tilde{f}_k e^{2\hat{z}_k} \to 1 + c_0 \equiv: r_0^2 \geq 0 \) locally uniformly on \( \mathbb{R}^2 \).

In view of the uniform volume bound
\[
(1 + o(1)) \int_{D_k} e^{2\hat{w}_k} \, dx = \int_{D_k} e^{2(\hat{w}_k + \hat{z}_k)} \, dx = \alpha_k \lambda_k \int_{B_R(0)} e^{2\nu_k} \, dx \leq C,
\]
from \cite{3}, Theorem 3, we then conclude that a subsequence \( \tilde{w}_k \to \tilde{w}_\infty \) locally uniformly, where \( \tilde{w}_\infty \) with \( \tilde{w}_\infty \leq 0 = \tilde{w}_\infty(0) \) solves the equation
\[
-\Delta \tilde{w}_\infty = r_0^2 e^{2\tilde{w}_\infty} \quad \text{on } \mathbb{R}^2,
\]
with \( \int_{\mathbb{R}^2} e^{2\tilde{w}_\infty} \, dx < \infty \). Hence \( r_0 > 0 \), and by the Chen-Li \cite{7} classification of all solutions to this equation we have \( w_\infty(x) := \tilde{w}_\infty(2x/r_0) + \log 2 = \log \left( \frac{2}{1+|x|^2} \right) \), and our claim follows.

In the remaining case we have \( 1 \leq C\alpha k^2 e^{2w_k}(x_k) \leq C \) uniformly in \( k \). In view of \cite[Theorem 4.5]{8} we then have \( |2w_k(x_k) + \log(\lambda_k)| \leq C \). Set \( r_k^2 = \lambda_k \) and rescale
\[
\tilde{w}_k(x) = w_k(r_k x) + \log(r_k).
\]

Then
\[
\tilde{w}_k \leq \tilde{w}_k(x_k/r_k) \leq C \quad \text{on } D_k = \{ x; |r_k x| < R \}, \quad k \in \mathbb{N}.
\]
Moreover, \( \tilde{w}_k \) satisfies the equation
\[
-\Delta \tilde{w}_k = \tilde{f}_k e^{2\tilde{w}_k} \quad \text{on } D_k,
\]
where a subsequence
\[
\tilde{f}_k(x) = \alpha_k \lambda_k^2 e^{2w_k(x_k)} (1 + \lambda_k^{-1} f_0(r_k x) + (\alpha_k \lambda_k)^{-1} h_k) \to r_0^2 (1 + (Ax, x))
\]
for some constant \( r_0 > 0 \) and with \( A = \frac{1}{2} Hess f(0) \). As before, from \cite{3}, Theorem 3, it follows that a subsequence \( \tilde{w}_k \to \tilde{w}_\infty \) locally uniformly, where \( w_\infty(x) := \tilde{w}_\infty(x/r_0) \leq C \) for \( A_0 = A/r_0^2 \) satisfies the equation
\[
-\Delta w_\infty = (1 + (A_0 x, x)) e^{2w_\infty} \quad \text{on } \mathbb{R}^2,
\]
with finite volume and finite total curvature
\[
\int_{\mathbb{R}^2} e^{2w_\infty} \, dx < \infty, \quad \int_{\mathbb{R}^2} |1 + (A_0 x, x)| e^{2w_\infty} \, dx < \infty.
\]
But Theorem \cite[4.5]{4.5} below rules out this case.

By the above characterization \cite[4.20]{4.20} of blow-up and \cite[4.19]{4.19}, at each blow-up point \( p_\infty^{(i)} \) with some constant \( 0 < r_0 \leq 1 \) we must have
\[
4\pi = \int_{\mathbb{R}^2} e^{2w_\infty} \, dx = r_0^2 \lim_{k \to \infty} \int_{B_{r_0}(0)} e^{2\tilde{w}_k} \, dx \leq r_0^2 \lim_{k \to \infty} \sup_{D_k} \int_{B_{r_k}(0)} e^{2\tilde{w}_k} \, dx \leq 8\pi r_0^2 \leq 8\pi.
\]
Thus there can be at most \( i_0 \leq 2 \) such blow-up points, and the proof is complete. \( \square \)

4.4. Ruling out slow blow-up. Entire solutions of Liouville’s equation with curvature functions of polynomial growth have been studied for instance by Cheng-Lin \cite{8}. Here we establish the following non-existence result.

**Theorem 4.5.** Suppose \( A \) is a negative definite and symmetric \( 2 \times 2 \) matrix. Then there is no solution \( w \in C^\infty(\mathbb{R}^2) \) of the equation
\[
-\Delta w = (1 + (Ax, x)) e^{2w} \quad \text{on } \mathbb{R}^2
\]
with \( w \leq C \) and such that the induced metric \( h = e^{2w} g_{\mathbb{R}^2} \) has finite volume and integrated curvature
\[
V_0 := \int_{\mathbb{R}^2} e^{2w} \, dx < \infty, \quad K_0 := \int_{\mathbb{R}^2} (1 + (Ax, x)) e^{2w} \, dx \in \mathbb{R}
\]
and hence also has finite total curvature
\[ \int_{\mathbb{R}^2} |1 + (Ax, x)| e^{2w} \, dx < \infty. \]

**Proof.** Writing \((1 + (Ax, x))e^{2w} =: F \in L^1(\mathbb{R}^2)\) for brevity, following Chen-Li [7] we introduce
\[ (4.23) \quad \hat{w}(x) = -\frac{1}{2\pi} \int_{\mathbb{R}^2} \left( \log |x - y| - \log |y| \right) F(y) \, dy \]
and note that in view of (4.22) we have \(|\hat{w}| \leq C \log(2 + |x|)\).

The function \(v := w - \hat{w}\) then is harmonic with \(v(x) \leq C + C \log(2 + |x|)\). Therefore, \(v\) must be constant. Indeed, by the mean value property of harmonic functions and the divergence theorem, in view of the bound
\[ |v| = 2v^+ - v \leq C - v + C \log(2 + |x|) \]
for any partial derivative \(\partial v\) and any \(x_0 \in \mathbb{R}^2\), \(R > 0\) we have
\[ |\partial v(x_0)| = \left| \int_{B_R(x_0)} \partial v \, dx \right| \leq CR^{-2} \int_{\partial B_R(x_0)} |v| \, do \]
\[ \leq CR^{-1} \left( C - v(x_0) + \log(2 + |x_0| + R) \right) \to 0 \text{ as } R \to \infty, \]
where \(f\) denotes the average and \(do\) denotes the one-dimensional Hausdorff measure. Hence \(w = \hat{w} + C\) for some \(C \in \mathbb{R}\), as claimed.

Next, observing that for any \(y \in \mathbb{R}^2\) there holds \(\log |x - y|/\log |x| \to 1 (|x| \to \infty)\). from (4.23) as \(|x| \to \infty\) we obtain
\[ (4.24) \quad \frac{\hat{w}(x)}{\log |x|} = -\frac{1}{2\pi} \int_{\mathbb{R}^2} \frac{\log |x - y| - \log |y|}{\log |x|} F(y) \, dy \]
\[ \to -\frac{1}{2\pi} \int_{\mathbb{R}^2} F \, dy = -\frac{K_0}{2\pi} := -\nu \in \mathbb{R}. \]

Since from (4.24) with error \(o(1) \to 0\) or any \(\mu > \nu - 1\) we also can bound
\[ \int_{\mathbb{R}^2 \setminus B_1(0)} |x|^{-2\mu} \, dx \leq C \int_{\mathbb{R}^2} |x|^2 e^{2\hat{w}} \, dx + C \]
\[ \leq C \int_{\mathbb{R}^2} |(Ax, x)| e^{2w} \, dx + C = C(V_0 - K_0) + C < \infty, \]
we conclude that \(\nu \geq 2\) and hence \(K_0 \geq 4\pi\).

Multiplying (4.21) with \(x \cdot \nabla w\) we find the identity
\[ \text{div} \left( \nabla w \cdot x \cdot \nabla w - \frac{x}{2} \left| \nabla w \right|^2 \right) + \text{div} \left( \frac{x}{2} (1 + (Ax, x)) e^{2w} \right) \]
\[ = (1 + (Ax, x)) e^{2w} + (Ax, x) e^{2w} = 2(1 + (Ax, x)) e^{2w} - e^{2w}. \]
Integrating over a ball \(B_R(0)\), we note that by finiteness of \(\|F\|_{L^1}\) we have
\[ R \int_{\partial B_R(0)} (1 + (Ax, x)) e^{2w} \, do \to 0 \]
as \(R \to \infty\) suitably. Also writing
\[ \int_{\partial B_R(x)} \frac{x}{|x|} \cdot (\nabla w \cdot x \cdot \nabla w - \frac{x}{2} \left| \nabla w \right|^2) \, do = \int_{\partial B_R(x)} \frac{|x \cdot \nabla w|^2 - |x \cdot \nabla w|^2}{2R} \, do, \]
where for any $x \in \mathbb{R}^2 \cong \mathbb{C}$ we denote as $x^+ = ix \in \mathbb{C}$ the vector $x$ rotated by 90 degrees, we then obtain

\begin{equation}
(4.25) \quad \frac{1}{2R} \int_{\partial B_R(0)} \left( |x \cdot \nabla w|^2 - |x^+ \cdot \nabla w|^2 \right) \, do + V_0 - 2K_0 \to 0
\end{equation}

as $R \to \infty$ suitably.

Differentiating (4.23) we find

\begin{equation}
(4.26) \quad x \cdot \nabla w(x) = x \cdot \nabla \tilde{w}(x) = -\frac{1}{2\pi} \int_{\mathbb{R}^2} \frac{x \cdot (x - y)}{|x - y|^2} F(y) \, dy = -\frac{K_0}{2\pi} + I(x),
\end{equation}

with

\[ I(x) := -\frac{1}{2\pi} \int_{\mathbb{R}^2} \frac{y \cdot (x - y)}{|x - y|^2} F(y) \, dy, \]

while

\begin{equation}
(4.27) \quad x^+ \cdot \nabla w(x) = x^+ \cdot \nabla \tilde{w}(x) = -\frac{1}{2\pi} \int_{\mathbb{R}^2} \frac{x^+ \cdot (x - y)}{|x - y|^2} F(y) \, dy = -\frac{1}{2\pi} \int_{\mathbb{R}^2} \frac{y^+ \cdot (x - y)}{|x - y|^2} F(y) \, dy =: II(x).
\end{equation}

We can estimate the error terms

\begin{equation}
(4.28) \quad \frac{1}{2R} \int_{\partial B_R(0)} \left( |I(x)|^2 + |II(x)|^2 \right) \, do \to 0
\end{equation}

as $R \to \infty$ suitably. Postponing the proof of (4.28), from (4.26) and (4.25) upon letting $R \to \infty$ suitably we then have

\begin{equation}
(4.29) \quad 0 = \frac{K_0^2}{4\pi} + V_0 - 2K_0 = \frac{K_0 - 8\pi}{4\pi} K_0 + V_0,
\end{equation}

and in view of $4\pi \leq K_0 \leq V_0$ we conclude that $K_0 = 4\pi = V_0$. Hence $A = 0$, which contradicts our assumptions and proves the claim.

It remains to show (4.28). Given any $\varepsilon > 0$ there exists $R_0 > 1$ such that

\[ \int_{\mathbb{R}^2 \setminus B_{R_0}(x)} |F(y)| \, dy \leq \varepsilon. \]

Let $|x| = 2R \geq 2R_0$. Observing that $|y| \leq |x - y| + |x|$ gives

\[ \frac{|y|}{|x - y|} \leq 2 \quad \text{for} \quad y \notin B_R(x), \]

we can bound

\[ \left| 2\pi I(x) + \int_{B_R(x)} \frac{y \cdot (x - y)}{|x - y|^2} F(y) \, dy \right| + \left| 2\pi II(x) + \int_{B_R(x)} \frac{y^+ \cdot (x - y)}{|x - y|^2} F(y) \, dy \right| \]

\[ \leq C \int_{\mathbb{R}^2 \setminus (B_R(x) \cup B_{R_0}(x))} \frac{|y|}{|x - y|} |F(y)| \, dy + C \frac{R_0}{2R - R_0} \int_{B_{R_0}(0)} |F(y)| \, dy \]

\[ \leq C\varepsilon + \frac{CR_0}{2R - R_0} \leq C\varepsilon \]

if $R \geq R_0$ is sufficiently large. Moreover, we have

\[ \left| \int_{B_R(x)} \frac{y \cdot (x - y)}{|x - y|^2} F(y) \, dy - \int_{B_R(x)} \frac{x \cdot (x - y)}{|x - y|^2} F(y) \, dy \right| \leq \int_{B_R(x)} |F(y)| \, dy \leq \varepsilon \]
and
\[ \int_{B_R(x)} \frac{y^\perp \cdot (x-y)}{|x-y|^2} F(y) dy = \int_{B_R(x)} \frac{z^\perp \cdot (x-y)}{|x-y|^2} F(y) dy \]

Next, changing coordinates to \( z = x - y \) we obtain
\[ \int_{B_R(x)} \frac{x \cdot (x-y)}{|x-y|^2} F(y) dy = \int_{B_R(0)} \frac{x \cdot z}{|z|^2} F(x-z) dz \]
\[ = \frac{1}{2} \int_{B_R(0)} \frac{x \cdot z}{|z|^2} (F(x-z) - F(x+z)) dz, \]
where we observe that
\[ \int_{B_R(0)} \frac{x \cdot z}{|z|^2} (F(x-z) + F(x+z)) dz = 0 \]
by symmetry. Similarly we have
\[ \int_{B_R(x)} \frac{x^\perp \cdot (x-y)}{|x-y|^2} F(y) dy = \frac{1}{2} \int_{B_R(0)} \frac{x^\perp \cdot z}{|z|^2} (F(x-z) - F(x+z)) dz. \]

Expanding
\[ (A(x \pm z), x \pm z) = (Ax, x) + (Az, z) \pm 2(Ax, z) \]
we then have
\[ F(x-z) - F(x+z) \]
\[ = (1 + (A(x-z, x-z)) e^{2w(x-z)} - (1 + (A(x+z, x+z)) e^{2w(x+z)}) \]
\[ = (1 + (Ax, x) + (Az, z)) (e^{2w(x-z)} - e^{2w(x+z)}) \]
\[ - 2(Ax, z) (e^{2w(x-z)} + e^{2w(x+z)}). \]

Note that we can bound
\[ \int_{B_R(0)} \frac{|x \cdot z|}{|z|^2} (|Ax, z| + |Az, z|) (e^{2w(x-z)} + e^{2w(x+z)}) dz \]
\[ \leq C \int_{B_R(0)} |x|^2 (e^{2w(x-z)} + e^{2w(x+z)}) dz \leq C \int_{B_R(x)} |F(y)| dy \leq C \epsilon. \]

Moreover, by (14.23) and the fact that \( \nu \geq 2 \), for any \( 2 < \mu < 3 \) we have
\[ \int_{B_R(0)} \frac{|x \cdot z|}{|z|^2} (e^{2w(x-z)} + e^{2w(x+z)}) dz \leq CR^{\mu-2\nu} \to 0 \]
as \( |x| = 2R \to \infty \). Thus we obtain
\[ |4\pi I(x) + \int_{B_R(0)} \frac{x^\perp \cdot z}{|z|^2} (Ax, x) (e^{w(x-z)} - e^{2w(x+z)}) dz| \leq C \epsilon, \]
and similarly
\[ |4\pi II(x) + \int_{B_R(0)} \frac{x^\perp \cdot z}{|z|^2} (Ax, x) (e^{2w(x-z)} - e^{2w(x+z)}) dz| \leq C \epsilon, \]
if \( R \geq R_0 \) is sufficiently large. But letting \( z = r \zeta \) with \( \zeta = e^{i\theta} \in S^1 \) and integrating for each \( z_0 = re^{i\theta_0} \in B_R(0) \) from \( \theta_0 \) to \( \theta_0 + \pi \) along a semi-circle with radius \( r \), we
have
\[ |e^{2w(x-z_0)} - e^{2w(x+z_0)}| \leq \left| \int_0^\pi 2z \cdot \nabla w(x + z) e^{2w(x+z)} \, d\theta \right| \]
\[ \leq C \sup_{|z|=r} |\nabla w(x + z)| \int_{\partial B_r(0)} e^{2w(x+z)} \, d\sigma. \]
Hence there results
\[ |I(x)| + |II(x)| \leq C \sup_{|z| \leq R} |\nabla w(x + z)| \int_{B_R(0)} |x|^3 e^{2w(x+z)} \, dz + C\varepsilon \]
(4.30)
\[ \leq C \sup_{y \in B_R(x)} |y| |\nabla w(y)| \int_{B_R(0)} |F(y)| \, dy + C\varepsilon \]
\[ \leq C\varepsilon \sup_{y \in B_R(x)} |y| |\nabla w(y)| + C\varepsilon. \]
But from (4.23) and (4.24) for any \( 3 < \mu < 4 \) with corresponding \( 0 < \alpha = 2\nu - \mu \) and any sufficiently large \( |x| = 2R \geq 2R_1 = 2R_1(\mu) \) we have
\[ |\nabla w(x)| = |\nabla w(x)| = \int_{\mathbb{R}^2} \frac{x-y}{|x-y|^2} F(y) \, dy \]
\[ \leq \int_{\mathbb{R}^2 \setminus B_R(x)} \frac{|F(y)|}{|x-y|} \, dy + \int_{B_R(x)} \frac{|F(y)|}{|x-y|} \, dy \leq CR^{-1} + CR^{\mu-2\nu} \leq CR^{-\alpha}. \]
Hence for any \( 0 < \alpha < 1 \) the number \( \sup_{y \in \mathbb{R}^2} |y|^\alpha |\nabla w(y)| \) is attained. But from (4.20), (4.27), and (4.30) for any \( 0 < \alpha < 1 \) with a constant \( C_2 > 0 \) independent of \( \alpha \) we have
\[ |x|^\alpha |\nabla w(x)| \leq \left( \frac{K_0}{2\pi} + |I(x)| + |II(x)| \right) |x|^{\alpha-1} \]
(4.31)
\[ \leq \left( \frac{K_0}{2\pi} + C_2\varepsilon \sup_{y \in B_R(x)} |y| |\nabla w(y)| \right) |x|^{\alpha-1} \]
\[ \leq \frac{K_0}{2\pi} |x|^{\alpha-1} + C_2\varepsilon \sup_{|y| \geq R} |y|^\alpha |\nabla w(y)|, \]
where \( \varepsilon \to 0 \) as \( |x| = 2R \to \infty \). Choose \( R_2 > 1 \) such that \( C_2\varepsilon < 1/2 \) for \( R \geq R_2 \) and set
\[ \Phi_\alpha(R) = \sup_{|y| \geq R} |y|^\alpha |\nabla w(y)|, \quad R \geq R_2. \]
Then, upon taking the supremum with respect to \( |x| \geq 2R_2 \) we obtain
\[ \Phi_\alpha(2R_2) \leq \frac{K_0}{2\pi} + \frac{1}{2} \Phi_\alpha(R_2) \leq \frac{K_0}{2\pi} + \frac{1}{2} \Phi_\alpha(2R_2) + \frac{1}{2} \sup_{R_0 \leq |y| \leq 2R_2} |y| |\nabla w(y)|. \]
Absorbing the second term on the right on the left side of this inequality and passing to the limit \( \alpha \uparrow 1 \), finally, we find the uniform bound
\[ |y| |\nabla w(y)| \leq \lim_{\alpha \uparrow 1} \Phi_\alpha(2R_2) \leq \frac{K_0}{\pi} + \sup_{R_0 \leq |y| \leq 2R_0} |y| |\nabla w(y)| < \infty. \]
for every \( |y| \geq 2R_2 \), which in view of (4.30) concludes the proof of (4.28). \( \square \)
5. "Bubbling" along the flow

Of course it is unreasonable to expect that Theorem 4.4 also holds true for non-minimizing critical points or even for Palais-Smale sequences of $E$ in $C^*$ for small $\lambda > 0$. However, our derivation of the bounds (4.7) for total curvature is sufficiently flexible to allow obtaining similar bounds for metrics evolving under the prescribed curvature flow for $f_\lambda$ when $t \to \infty$ in this limit regime. Moreover, the bounds from Lemmas 2.3 and 3.1 yield precisely the control on the error terms resulting from the presence of the time derivative that is required in Theorem 4.4.

5.1. Bounds for total curvature along the flow. Let $f_0 \leq 0$ be a smooth, non-constant function with max $f_0 = 0$ having only non-degenerate maxima $p_0$ where $f_0(p_0) = 0$, and for $0 < \lambda < \lambda_0$ let $f_\lambda = f_0 + \lambda$ as above where $\lambda_0 > 0$ is such that $f_{\lambda_0}$ changes sign and satisfies (1.3). Given $0 < \lambda < \lambda_0$ we fix a number $\delta_0 = \delta_0(\lambda) > 0$. (In fact, we may choose $\delta_0 = 1$ for all $\lambda$.) For any $\delta \in [\delta_0, 0]$ we then consider initial data $u_0^\delta \in C^*$ with

\begin{equation}
E(u_0^\delta) \leq \beta_\lambda + \delta^2,
\end{equation}

and let $u_\lambda^\delta = u_\lambda^\delta(t)$ with $\alpha_\lambda^\delta = \alpha_\lambda^\delta(t)$ be the smooth solution of (1.6), (1.7) for $f_\lambda$ with data $u_\lambda^\delta(0) = u_0^\delta$ guaranteed by Theorem 1.2. Then the following holds.

Lemma 5.1. We have

\[
\liminf_{\lambda \to 0} \limsup_{\delta \to 0} \limsup_{t \to \infty} \int_{M \times [t]} |K_{\alpha_\lambda^\delta}| \mu_{\alpha_\lambda^\delta} \leq 2 \liminf_{\lambda \to 0} \limsup_{\delta \to 0} \limsup_{t \to \infty} (\lambda \alpha_\lambda^\delta(t)) \leq 4 \liminf_{\lambda \to 0} (\beta_\lambda) \leq 16\pi.
\]

Proof. For any $0 < \lambda < \lambda_0$, $\delta \in [\delta_0(\lambda), 0]$ let $u_\lambda^\delta$ as above. We claim that for each $t \geq 0$ we have $u_\lambda^\delta + \delta f_\lambda \in C_\mu$ with $\mu = \mu(t) > \lambda$ as in (4.3) above, when $\delta_0 = \delta_0(\lambda) > 0$ is sufficiently small. Indeed, for each $t \geq 0$ let $\delta' = \delta'(t), \delta'' = \delta''(t) \in \delta, 0$ such that

\[
\int_M f_\lambda e^{2(u_\lambda^\delta + \delta f_\lambda)} \mu_{g_\lambda} = 2\delta \int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta' f_\lambda)} \mu_{g_\lambda}
\]

and

\[
\int_M e^{2(u_\lambda^\delta + \delta f_\lambda)} \mu_{g_\lambda} = 1 + 2\delta \int_M f_\lambda e^{2u_\lambda^\delta} \mu_{g_\lambda} + 2\delta^2 \int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta' f_\lambda)} \mu_{g_\lambda} = 1 + 2\delta^2 \int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta'' f_\lambda)} \mu_{g_\lambda}
\]

\[
to obtain u_\lambda^\delta + \delta f_\lambda \in C_\mu with
\]

\begin{equation}
(5.2) \quad \mu = \lambda - \frac{2\delta \int_M f_\lambda^2 e^{2u_\lambda^\delta + \delta' f_\lambda} \mu_{g_\lambda}}{1 + 2\delta^2 \int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta'' f_\lambda)} \mu_{g_\lambda}} > \lambda.
\end{equation}

Note that in view of the energy bound (5.1) the argument used to prove Lemma 2.3 gives a uniform in time lower bound

\[
\int_M f_\lambda^2 e^{2u_\lambda^\delta} \mu_{g_\lambda} \geq \left( \int_M f_\lambda \mu_{g_\lambda} \right)^2 / \int_M e^{-2u_\lambda^\delta} \mu_{g_\lambda} \geq c = c(\lambda) > 0
\]
for any \(0 < \lambda < \lambda_0\) and sufficiently small \(\delta_0 = \delta_0(\lambda) > 0\), uniformly in \(\delta \in ]-\delta_0,0[\). In addition, clearly we can bound
\[
\int_M f_\lambda^2 e^{2u_\lambda^\delta} \, d\mu_{g_0} \leq \|f_\lambda\|^2_{L^\infty} \int_M e^{2u_\lambda} \, d\mu_{g_0} = \|f_\lambda\|^2_{L^\infty}
\]
and we have
\[
e^{-2\delta_0 \|f_\lambda\|_{L^\infty}} \leq \int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta' f_\lambda)} \, d\mu_{g_0} / \int_M f_\lambda^2 e^{2u_\lambda} \, d\mu_{g_0} \leq e^{2\delta_0 \|f_\lambda\|_{L^\infty}}
\]
uniformly for all \(t \geq 0\) and \(\delta, \delta' \in ]-\delta_0,0[\). In consequence we have
\[
C^{-1} \|f_\lambda\|_{L^\infty} \leq |\mu - \lambda| \leq C \|f_\lambda\|_{L^\infty}
\]
with a uniform constant \(C > 0\) independent of \(t \geq 0\) and \(\delta \in ]-\delta_0,0[\). Moreover, we obtain uniform bounds for \(\alpha_\lambda^\delta(t)\) and \(u_\lambda^\delta(t)\) as in Lemmas 2,4 and 2.5.

Next, as before we expand
\[
E(u_\lambda^\delta + \delta f_\lambda) = E(u_\lambda^\delta) + \delta \int_M \nabla u_\lambda^\delta \cdot \nabla f_\lambda \, d\mu_{g_0} + \delta^2 E(f_\lambda)
\]
with \(E(f_\lambda) = E(f_0)\). Using (1.10) to write
\[
\int_M \nabla u_\lambda^\delta \cdot \nabla f_\lambda \, d\mu_{g_0} = \int_M (-\Delta_{g_\delta} u_\lambda^\delta) f_\lambda \, d\mu_{g_0} = \int_M K_{g_\delta} f_\lambda e^{2u_\lambda^\delta} \, d\mu_{g_0}
\]
\[
= \alpha_\lambda^\delta(t) \int_M f_\lambda^2 e^{2u_\lambda^\delta} \, d\mu_{g_0} - \int_M u_\lambda^\delta f_\lambda e^{2u_\lambda^\delta} \, d\mu_{g_0}
\]
and recalling that with \(F(t) = F_\lambda^\delta(t)\) on account of Lemma 3.1 and (1.12) we can bound
\[
|\int_M u_\lambda^\delta f_\lambda e^{2u_\lambda^\delta} \, d\mu_{g_0}| \leq \|f_\lambda\|_{L^\infty} F^{1/2}(t) \to 0 \text{ as } t \to \infty,
\]
with error \(o(1) \to 0\) as \(t \to \infty\) for each \(t \geq 0\) we find
\[
\beta_\mu \leq E(u_\lambda^\delta + \delta f_\lambda) \leq E(u_\lambda^\delta) + \delta \alpha_\lambda^\delta \int_M f_\lambda^2 e^{2u_\lambda^\delta} \, d\mu_{g_0} + \delta^2 E(f_0) + o(1).
\]
But from (5.2) we obtain
\[
2\delta \int_M f_\lambda^2 e^{2u_\lambda^\delta} \, d\mu_{g_0} = \frac{(1 + 2\delta^2 \int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta' f_\lambda)} \, d\mu_{g_0}) \int_M f_\lambda^2 e^{2u_\lambda^\delta} \, d\mu_{g_0}}{\int_M f_\lambda^2 e^{2(u_\lambda^\delta + \delta' f_\lambda)} \, d\mu_{g_0}},
\]
and with a uniform constant \(C > 0\) independent of \(t \geq 0\) and \(\delta \in ]-\delta_0,0[\) there results
\[
|2\delta \int_M f_\lambda^2 e^{2u_\lambda^\delta} \, d\mu_{g_0} - 1| \leq C\delta \leq C|\lambda - \mu|.
\]
Thus, and using (5.1), we finally arrive at the estimate
\[
\beta_\mu \leq \beta_\lambda - \frac{\alpha_\lambda^\delta}{2}(\mu - \lambda) + O((\mu - \lambda)^2) + o(1)
\]
and with \(t \to \infty\), we have \(\mu \downarrow \lambda\) as \(t \to \infty\), and for almost every \(0 < \lambda < \lambda_0\) we obtain
\[
\limsup_{\delta \to 0} \limsup_{t \to \infty} \alpha_\lambda^\delta(t) \leq 2 \lim_{\mu \downarrow \lambda} \frac{\beta_\lambda - \beta_\mu}{\mu - \lambda} = 2|\beta_\lambda^\delta|.
\]
Choosing $\delta$ We may then fix a sequence $(5.3)$ sup

We find the uniform bound

Multiplying with $\lambda > 0$, as in $(4.3)$ we find

But from $(1.6)$ and recalling that we may bound $|f_\lambda| \leq -f_0 + \lambda = -f_\lambda + 2\lambda$, with the help of $(1.4)$ we obtain the bound

$\int_M |K_{g^\delta_\lambda} | \, d\mu_{g^\delta_\lambda} \leq \int_M |u_{\lambda,t}^\delta \, d\mu_{g^\delta_\lambda} + \alpha^\delta_\lambda \int_M |f_\lambda| \, d\mu_{g^\delta_\lambda} \leq F^{1/2}(t) + 2\lambda \alpha^\delta_\lambda(t)$

at any time $t \geq 0$, and our claim follows.

5.2. “Bubbling” of the prescribed curvature flow. By Lemma 5.1 there is a sequence $\lambda_k \downarrow 0$ such that

We may then fix a sequence $\delta_k \uparrow 0$ satisfying

Choosing $\delta = \delta_k$ for each $k \in \mathbb{N}$, finally, for suitable $T_k \to \infty$ with $F_k(t) = F^{\delta_k}_{\lambda_k}(t)$ we find the uniform bound

$(5.3) \sup_{t \geq T_k} \int_{M \times \{t\}} |K_{g^\delta_{\lambda_k}} | \, d\mu_{g^\delta_{\lambda_k}} \leq 2 \sup_{t \geq T_k} (\lambda_k \alpha^\delta_{\lambda_k}(t) + F_k(t))^{1/2} \leq 16\pi + 5/k$

for all $k \in \mathbb{N}$.

Thus, if for each $k \in \mathbb{N}$ we let $v_k = u^\delta_{\lambda_k}(t_k)$, satisfying $(4.5)$ with $\alpha_k = \alpha^\delta_{\lambda_k}(t_k)$ and $h_k = u^\delta_{\lambda_k,\lambda}(t_k)$ for $t_k \geq T_k$, our Theorem 4.4 applies and we find that the flows $(u^\delta_{\lambda_k}(t))_{t \geq T_k, k \in \mathbb{N}}$ blow up spherical “bubbles” as $t \to \infty$.

6. The degenerate case

Conceivably, as in the analysis $[23]$ of “bubbling” solutions to the prescribed curvature flow on $S^2$, also the prescribed curvature flow on the torus will only blow up in a single “bubble” whose center approximately moves in direction of the negative gradient of the prescribed curvature function $f$, similar to $[23]$, Proposition 4.9.

Moreover, if one could establish such a result even in the case when the maxima of $f_0$ are allowed to be degenerate, one could use this to give an example of a prescribed curvature flow with non-unique subsequential limits as $t \to \infty$ (in contrast with the analytic case studied by Nguo-Xu [17]) by following the construction of Topping [25], p. 609, for the heat flow of harmonic maps.

6.1. A scenario for non-uniqueness. Recall that Topping [25] considered the heat flow of harmonic maps from the standard 2-sphere $S^2$ to $\mathbb{R}^2 \times S^2$ or $T^2 \times S^2$, where the target is endowed with the warped metric $d\mu_{\mathbb{R}^2}(x) + f(x)d\mu_{S^2}(y)$ for suitable $f \geq 1$. With the fixed harmonic component $u_0 = id: S^2 \to S^2$ and with $z = z(t)$ satisfying $dz/dt = -\nabla f(z)$ then $u(x,t) = (z(t), u_0(x))$ is a solution to the flow. Letting $f = 1 - f_0$, where in polar coordinates $(r, \theta)$ on a Euclidean disc $B_2(0)$ the function $f_0$ is given by $f_0(r, \theta) = 0$ for $r \leq 1$ and by

$$f_0(r, \theta) = -e^{-r^2}(\sin(\frac{1}{r-1} + \theta) + 2)$$

\[\text{Note, however, that in [23] we only consider flows that not even subsequentially converge.}\]
for $r > 1$, scaled and smoothly extended to the torus, for suitable data $z_0 = z(0)$
Topping then obtains a flow where the “center” $z(t)$ follows a “spiralling groove on
a gramophone record” and thus has non-unique subsequential limits as $t \to \infty$.

6.2. “Bubbling” in the degenerate case. Given a smooth function $f_0$ with
$f_0 \leq 0 = \max f_0$, let $M_0 = \{ p \in M; f_0(p) = 0 \}$ and set $d(p) = \text{dist}(p, M_0)$. As
a possible replacement of the non-degeneracy condition in Theorem 4.4 that also applies in the case when $f_0$ may have degenerate maxima we propose the following condition.

**Condition A:** There exist $d_0 > 0$ and $A_0 > 0$ such that, letting
\[ K_0 = \{ x = (x^1, x^2) \in \mathbb{R}^2; |x^1| < x^2, |x| < d_0 \}, \]
for any $p \in M$ with $0 < d(p) < d_0$ there is a rotated copy $K_p \subset \mathbb{R}^2$ of $K_0$ such that
in Euclidean coordinates $x$ around $p = 0$ there holds
\[ A_0 \inf_{x \in K_p} |f_0(x)| \geq |f_0(p)|. \]  

Clearly, Condition A is satisfied by any function $f_0$ with only non-degenerate
maximum points. Moreover, the function $f_0$ given by (6.1) satisfies Condition A
(with $A_0 = 3$).

We then have the following result.

**Theorem 6.1.** Let $f_0 \leq 0$ be a smooth, non-constant function with $\max f_0 = 0$
satisfying Condition A with constants $d_0, A_0 > 0$. Then for any $v_k$ as in Lemma
6.3 above for suitable $i_0 \in \mathbb{N}$, $r_k(i) \downarrow 0$, $p_k(i) \to p_\infty(i) \in M$ with $f_0(p_\infty(i)) = 0$, $1 \leq i \leq i_0$,
the following holds.

i) We have $v_k \to -\infty$ locally uniformly on $M_\infty = M \setminus \{ p_\infty(i); 1 \leq i \leq i_0 \}$.

ii) For each $1 \leq i \leq i_0$ in Euclidean coordinates $x$ around $p_k(i) = 0$ we have
\[ \lim_{r_k(i) \downarrow 0} v_k(r_k(i) x) + \log r_k(i) \to w_\infty(x) \]
in $H^2_{loc}$ on $\mathbb{R}^2$, where $w_\infty$ induces a metric $g_\infty = e^{2w_\infty} g_{\mathbb{R}^2}$ on $\mathbb{R}^2$ of locally bounded
curvature, and $1 \leq i_0 \leq 4$.

**Proof.** As in the proof of Theorem 4.4 we have concentration of curvature in the sense that for a subsequence $k \to \infty$ there holds
\[ K^+_g e^{2v_k} d\mu_{g_k} \to K_+ + \sum_{i \in I} \gamma_i \delta_{p_\infty(i)} \]
weakly-* in the sense of measures, with a measure $K_+ \geq 0$ on $M$ having no atoms
and with at most countably many atoms of weight $\gamma_i > 0$, $i \in I \subset \mathbb{N}$, and where
$\gamma_i \geq \pi/2$ if only if $1 \leq i \leq i_0$ for some $i_0 \geq 1$. In particular, with error $o(1) \to 0$ as
$k \to \infty$ we have
\[ \pi/2 - o(1) \leq \alpha_k \lambda_k \leq 8\pi + o(1) \quad \forall k \in \mathbb{N}. \]

analogous to (4.14). Moreover, the proof of statement i) above is identical with the proof of the corresponding statement in Theorem 4.4 and we only have to show
that also with the weaker Condition A on $f_0$ we are able to extract “bubbles” from
the metrics $g_k = e^{2v_k} g_\mathbb{R}^2, k \in \mathbb{N}$, and estimate their number.
ii) Thus let $p_0 = p_0(i)$ for some $i \leq i_0$. With $\tilde{h}_k = \int_M h_k e^{2v_k} d\mu_{g_k}$ satisfying $|\tilde{h}_k| \leq \varepsilon_k \to 0 (k \to \infty)$ we split $v_k = w_k + z_k$, where

$$-\Delta_{g_k} z_k = (h_k - \tilde{h}_k)e^{2v_k} \quad \text{with} \quad \int_M z_k d\mu_{g_k} = 0,$$

so that $\|z_k\|_{L^\infty} \to 0$ as $k \to \infty$ as before. In Euclidean coordinates around $p_0 = 0$ then for any sufficiently small $R > 0$ we again can find points $x_k \to 0$ and radii $r_k \to 0$ such that

$$(6.4) \quad \int_{B_{\sqrt{k}}(x_k)} K^+_{g_k} d\mu_{g_k} = \sup_{x_0 \in B_R(0)} \int_{B_{\sqrt{k}}(x_0)} K^+_{g_k} d\mu_{g_k} = \pi/3.$$  

Define

$$\tilde{w}_k(x) = w_k(x_k + r_k x) + \log r_k, \quad \tilde{z}_k(x) = z_k(x_k + r_k x)$$

on $D_k = \{x; \ |x_k + r_k x| < R\}$, where again we note that the domains $D_k$ exhaust $\mathbb{R}^2$ as $k \to \infty$. There holds the equation

$$-\Delta \tilde{w}_k = (\alpha_k f \lambda_k(x_k + r_k x) + \tilde{h}_k)e^{2(\tilde{w}_k + \tilde{z}_k)} = f_k e^{2\tilde{z}_k} e^{2\tilde{w}_k}$$

on $D_k$, where

$$\tilde{f}_k(x) = \alpha_k f \lambda_k(x_k + r_k x) + \tilde{h}_k = \alpha_k \lambda_k (1 + \lambda_k^{-1} f_0(x_k + r_k x) + (\alpha_k \lambda_k)^{-1} \tilde{h}_k).$$

Splitting $\tilde{w}_k = \tilde{w}_k^{(+)} + \tilde{w}_k^{(0)} + \tilde{w}_k^{(-)}$ on any ball $B = B_1(x_0)$, where $\Delta \tilde{w}_k^{(0)} = 0$ in $B$ with $\tilde{w}_k^{(0)} = w_k$ on $\partial B$, and where $\tilde{w}_k^{(\pm)} \in H^1_0(B)$ with $\Delta \tilde{w}_k^{(\pm)} = (\Delta \tilde{w}_k)^\pm$, then with $\gamma = 1/20$ similar to the proof of Lemma 4.3 from [6.4] and [4.9] we obtain uniform bounds

$$\|e^{\tilde{w}_k^{(+)}}\|_{L^p(B)} + \|e^{-\gamma \tilde{w}_k^{(-)}}\|_{L^p(B)} \leq C \quad \text{for any} \ 1 \leq p < 4,$$

as well as

$$\|\tilde{w}^{(\pm)}_k\|_{W^{1,p}(B)} \leq C \quad \text{for any} \ 1 \leq p < 2.$$  

Moreover, estimating $\tilde{w}_k^{(0)} \leq \tilde{w}_k - \tilde{w}_k^{(-)}$, for any disc $D \subset B$ we again find a uniform bound

$$\exp \left( \int_D \gamma \tilde{w}_k^{(0)} \, dx \right) \leq \int_D e^{\gamma \tilde{w}_k^{(0)}} \, dx \leq C \left( \int_B e^{2\gamma \tilde{w}_k^{(0)}} \, dx \cdot \int_B e^{2\gamma \tilde{z}_k^{(-)}} \, dx \right)^{1/2} \leq C.$$

Continuing to argue as in the proof of Lemma 4.3 then we have a uniform bound $\tilde{w}_k^{(0)} \leq C_1$ on $B_{2/3}(x_0)$, and either $|\tilde{w}_k^{(0)}| \leq C$ on $B_{1/2}(x_0)$ for all $k \in \mathbb{N}$, or there exists a subsequence such that $\tilde{w}_k^{(0)} \to -\infty$ uniformly on $B_{1/2}(x_0)$ as $k \to \infty$ suitably. In any event, for any ball $B$, upon covering $B$ with finitely many balls $B_{1/2}(x_j)$, $1 \leq j \leq J$, and estimating $\tilde{w}_k \leq \tilde{w}_k^{(+) + \tilde{w}_k^{(-)} \leq \tilde{w}_k^{(+)} + C_1$ on each ball, we find

$$\|e^{\tilde{w}_k}\|_{L^p(B)} \leq C \sum_{1 \leq j \leq J} \|e^{\tilde{w}_k^{(+)}}\|_{L^p(B_{1/2}(x_j))} \leq C \quad \text{for any} \ 1 \leq p < 4.$$  

Choosing $p = 3$, as before we conclude that $\tilde{w}_k^{(+)} \leq C \|\tilde{w}_k^{(+)}\|_{W^{2,3/2}} \leq C$ uniformly on any $B$, if $k \in \mathbb{N}$ is sufficiently large.

In particular, letting $B = B_1(0)$ and bounding $\tilde{w}_k \leq \tilde{w}_k^{(+)} + w_k^{(0)} \leq C + w_k^{(0)}$ on each $B_{1/2}(x_j)$ covering $B$, if we suppose that $w_k^{(0)} \to -\infty$ uniformly on some $B_{1/2}(x_{j_0})$ we find that also $\tilde{w}_k \to -\infty$ uniformly on $B_{1/2}(x_{j_0})$ and hence on every
By (6.3) we may assume that
\[ \| \text{and} \| \]
and (1.4) for any \( |\tilde{A}| \)
\( (6.8) \)
From (6.7) and (6.8) there then results a contradiction.

Passing to the limit
\( L \)
loc
and almost everywhere on
\( B \)
Fatou’s lemma now yields that for any \( L \in \mathbb{N} \) we have
\[ \int_{B_L(0)} e^{2\tilde{u}_k} \, dx \leq \liminf_{k \to \infty} \int_{B_L(0)} e^{2(\tilde{u}_k + \tilde{z}_k)} \, dx \leq \liminf_{k \to \infty} \int_{M} e^{2\tilde{w}_k} \, d\mu_y = 1. \]

Passing to the limit \( L \to \infty \) we find \( e^{2\tilde{u}_\infty} \in L^1(\mathbb{R}^2) \) with
\[ \int_{\mathbb{R}^2} e^{2\tilde{u}_\infty} \, dx = \lim_{L \to \infty} \int_{B_L(0)} e^{2\tilde{w}_k} \, dx \leq 1. \]

For \( k \in \mathbb{N} \) set \( \tilde{f}_0(x) := \lambda_k^{-1} f_0(x) + r_k x \) so that
\[ \tilde{f}_k(x) = \alpha_k f_\lambda(x + r_k x) + \tilde{h}_k = \alpha_k \lambda_k (1 + \tilde{f}_0) + (\alpha_k \lambda_k)^{-1} \tilde{h}_k. \]

By (6.3) we may assume that \( \alpha_k \lambda_k \to \mu > 0 \) as \( k \to \infty \). Recalling that \( |\tilde{h}_k| \to 0 \)
and \( \|\tilde{z}_k\|_{L^\infty} \to 0 \) as \( k \to \infty \), and writing \( |\tilde{f}_0| = -\tilde{f}_0 = 1 - (1 + \tilde{f}_0) \), by Fatou’s lemma and (1.4) for any \( L \in \mathbb{N} \) we have
\[ \mu \int_{B_L(0)} \liminf_{k \to \infty} \frac{1}{|\tilde{f}_0|} \int_{B_L(0)} e^{2\tilde{w}_k} \, dx \leq \liminf_{k \to \infty} \int_{B_L(0)} \alpha_k \lambda_k |\tilde{f}_0| e^{2\tilde{w}_k} \, dx \]
\( (6.7) \)
\[ \leq \liminf_{k \to \infty} \int_{B_L(0)} (\alpha_k \lambda_k - \tilde{f}_k) e^{2\tilde{w}_k} \, dx \leq \liminf_{k \to \infty} \int_{M} (\alpha_k \lambda_k - \alpha_k f_\lambda) e^{2\tilde{w}_k} \, d\mu_y \]
\[ = \liminf_{k \to \infty} \int_{M} \alpha_k \lambda_k e^{2\tilde{w}_k} \, d\mu_y = \mu \leq 8\pi < \infty. \]

We can use this result together with Condition A to show that \( \tilde{f}_0 \) is locally bounded. Indeed, suppose that for some sequence \( y_k \to y_0 \) in \( \mathbb{R}^2 \) there holds
\[ |\tilde{f}_0(y_k)| = |f_0(y_k)| / \lambda_k \to \infty \text{ as } k \to \infty, \]
where \( q_k = x_k + r_k y_k, k \in \mathbb{N} \). Then \( q_k \to 0 \) and hence \( d(q_k) \to 0 \) as \( k \to \infty \), and we may assume that \( d(q_k) < d_0 \) for all \( k \). By Condition A there exist cones \( K_k = K_{q_k} \) with vertex at \( q_k \) such that
\[ A_0 \inf_{y \in Q_k} |\tilde{f}_0(y)| = A_0 \lambda_k^{-1} \inf_{q \in K_k} |f_0(q)| \geq \lambda_k^{-1} |f_0(q_k)| = |\tilde{f}_0(y_k)| \to \infty \]
as \( k \to \infty \), where with a suitable labelling of coordinates
\[ Q_k = \{ y; x_k + r_k y \in K_k \} \]
\[ = \{ y = (y', y''); |y' - y'_{\lambda_k}| < y' - y_{\lambda_k}; |y - y_k| < d_0 / r_k \}. \]
From (6.7) and (6.8) there then results a contradiction.
Hence we may assume that $\tilde{f}_k e^{2\tilde{w}_k} \rightharpoonup \mu (1 + \tilde{f}_0) e^{2\tilde{w}_0}$ weakly-* in the sense of measures, where $\tilde{f}_0 \leq 0$ is locally bounded from below. Setting
\[
\tilde{F}_\infty := \mu (1 + \tilde{f}_0) e^{2\tilde{w}_0}
\]
with $\int_{\mathbb{R}^2} |\tilde{F}_\infty| dx \leq 16\pi$, then $\tilde{w}_\infty$ weakly solves the equation $-\Delta \tilde{w}_\infty = \tilde{F}_\infty$ on $\mathbb{R}^2$.

In order to obtain a lower bound on the volume of the metric $\tilde{g}_\infty = e^{2\tilde{w}_\infty} g_{\mathbb{R}^2}$ we once more follow Chen-Li [7] and set
\[
w_\infty = -\frac{1}{2\pi} \int_{\mathbb{R}^2} (\log |x - y| - \log |y|) \tilde{F}_\infty(y) dy
\]
with $|w_\infty| \leq C \log(2 + |x|)$ and satisfying
\[
(6.9) \quad \frac{w_\infty(x)}{\log |x|} = -\frac{1}{2\pi} \int_{\mathbb{R}^2} \frac{\log |x - y| - \log |y|}{\log |x|} \tilde{F}_\infty(y) dy \to -\frac{1}{2\pi} \int_{\mathbb{R}^2} \tilde{F}_\infty dy =: -\nu
\]
as $|x| \to \infty$ for some $|\nu| \leq 8$. The mean value property of harmonic functions and the bound $\tilde{w}_\infty - w_\infty \leq C + C \log(2 + |x|)$ then again yield the existence of a constant $C \in \mathbb{R}$ such that $w_\infty = \tilde{w}_\infty + C$. Since $e^{2\tilde{w}_\infty} \in L^1(\mathbb{R}^2)$ in view of (6.6), we then also have $e^{2w_\infty} \in L^1(\mathbb{R}^2)$. It follows that $\nu \geq 1$, and we can estimate
\[
\mu \int_{\mathbb{R}^2} e^{2\tilde{w}_\infty} dx \geq \int_{\mathbb{R}^2} \tilde{F}_\infty dx \geq 2\pi.
\]
Since $\mu \leq 8\pi$ we conclude that $\int_{\mathbb{R}^2} e^{2\tilde{w}_\infty} dx \geq 1/4$. But the volumes of all bubbles obtained by rescaling the normalized metrics can add up to at most 1. Hence there can be at most four points where bubbles form, and $i_0 \leq 4$. \hfill \Box

References


[18] Ngô, Qu’oc Anh; Xu, Xingwang: private communication.

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