

## Solutions for Toda systems on Riemann surfaces

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*Dedicated to Professor Ding Weiyue on the occasion of his 60th birthday*

**Abstract.** In this paper we study the solutions of Toda systems on Riemann surface in the critical case, proving a sufficient condition for existence.

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### 1. Introduction

Let  $(\Sigma, g)$  be a compact Riemann surface with unit area 1. Ding-Jost-Li-Wang [8] studied the differential equation  $\Delta u = 8\pi - 8\pi he^u$  on  $(\Sigma, g)$ , the so-called Kazdan-Warner problem [17] related to the Abelian Chern-Simons model (see [3, 4, 6, 5, 7, 1, 2, 9, 10, 11, 23, 13, 14, 24, 21], etc). They pursued a variational approach to the problem, trying to minimize the functional

$$J(u) = \frac{1}{2} \int_{\Sigma} |\nabla u|^2 dV_g + 8\pi \int_{\Sigma} u dV_g - 8\pi \log \int_{\Sigma} h e^u dV_g \geq C, \quad \text{in } H^{1,2}(\Sigma) \quad (1.1)$$

for some constant  $C > 0$ . Because it is the critical case of the Moser-Trudinger inequality (1.1), the analysis is subtle.

Let  $K$  denote the Cartan matrix for  $SU(N + 1)$ , *i.e.*

$$K = (a_{ij}) = \begin{pmatrix} 2 & -1 & 0 & \dots & \dots & 0 \\ -1 & 2 & -1 & 0 & \dots & 0 \\ 0 & -1 & 2 & -1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & \dots & -1 & 2 & -1 \\ 0 & \dots & \dots & 0 & -1 & 2 \end{pmatrix}.$$

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In this paper we consider the Toda systems on  $(\Sigma, g)$  which are related to the non-Abelian Chern-Simons model [22]:

$$-\Delta u_i = M_i \left( \frac{\exp(\sum_{j=1}^N a_{ij}u_j)}{\int_{\Sigma} \exp(\sum_{j=1}^N a_{ij}u_j)} - 1 \right), \quad \text{for } 1 \leq i \leq N.$$

If  $M_i < 4\pi$  Jost-Wang [16] proved the existence of solutions and in the case where  $\Sigma$  is a torus,  $N = 2$ ,  $\max\{M_1, M_2\} > 4\pi$  and  $\min\{M_1, M_2\} \neq 4\pi$ , Marcello-Margherita [20] proved the same result.

They studied the problem by considering for  $u_1, \dots, u_N \in H^{1,2}(\Sigma)$  the functional

$$\begin{aligned} \Phi_{(M_1, \dots, M_N)}(u_1, \dots, u_N) &= \frac{1}{2} \sum_{i,j=1}^N \int_{\Sigma} a_{ij}(\nabla u_i \nabla u_j + 2M_i u_j) dV_g \\ &\quad - \sum_{i=1}^N M_i \log \int_{\Sigma} \exp \left( \sum_{j=1}^N a_{ij}u_j \right) dV_g. \end{aligned} \tag{1.2}$$

Jost-Wang [16] proved that the functional has a lower bound if and only if

$$M_i \leq 4\pi, \quad \text{for } i = 1, 2, \dots, N.$$

Marcello-Margherita [20] obtained a non-minimizing critical point of the functional motivated by an earlier paper of Struwe-Tarantello [23]. The idea was later also used by Djadli and Malchiodi [12] to study the existence of conformal metrics with constant  $Q$ -curvature. It is clear that  $M_i = 4\pi$  is the critical case of the functional. Whether it admits minimizer is subtle. In this paper we study this problem. For simplicity, we consider only the case that  $N = 2$ , the general case need only more calculations. In our case the functional is

$$\begin{aligned} \Phi(u_1, u_2) &= \frac{1}{2} \sum_{i,j=1}^2 \int_{\Sigma} a_{ij}(\nabla u_i \nabla u_j + 8\pi u_j) dV_g \\ &\quad - \sum_{i=1}^2 4\pi \log \int_{\Sigma} \exp \left( \sum_{j=1}^2 a_{ij}u_j \right) dV_g, \end{aligned}$$

and the Toda systems is

$$-\Delta u_i = 4\pi \left( \frac{\exp \left( \sum_{j=1}^2 a_{ij}u_j \right)}{\int_{\Sigma} \exp \left( \sum_{j=1}^2 a_{ij}u_j \right)} - 1 \right), \quad \text{for } 1 \leq i \leq 2, \tag{1.3}$$

where  $a_{11} = a_{22} = 2$  and  $a_{12} = a_{21} = -1$ . The systems is equivalent to

$$-\Delta u_i = 4\pi \sum_{j=1}^2 a_{ij} \left( \frac{\exp(u_j)}{\int_{\Sigma} \exp(u_j)} - 1 \right), \quad \text{for } 1 \leq i \leq 2,$$

where  $a_{11} = a_{22} = 2$  and  $a_{12} = a_{21} = -1$ .

Our main result is as follows:

**Main Theorem.** *Let  $\Sigma$  be a compact Riemann surface with area 1. If the Gauss curvature  $K$  of  $\Sigma$  satisfies that*

$$\max_{p \in \Sigma} K(p) < 2\pi, \tag{1.4}$$

then  $\Phi(u_1, u_2)$  has a minimizer.

We consider the sequence of minimizers  $u^\epsilon = (u_1^\epsilon, u_2^\epsilon)$  of  $\Phi_{(4\pi-\epsilon, 4\pi-\epsilon)}$  for small  $\epsilon > 0$ . Then  $u^\epsilon$  satisfies a Toda type systems. If  $u^\epsilon$  converges to  $u^0 = (u_1^0, u_2^0)$  in  $H_2 := H^{1,2}(\Sigma) \times H^{1,2}(\Sigma)$ , then it is clear that  $\Phi(u^0) = \inf_{u \in H_2} \Phi(u)$ , i.e.,  $u^0$  is a minimizer of  $\Phi$ . If  $u^\epsilon$  does not converge in  $H_2$ , in this case, we say that  $u^\epsilon$  blows up. Then there are two cases happened according to Jost-Wang’s result. For each case, we derive a delicate lower bound of  $\Phi$  which is one of the main points in this paper. We apply capacity to calculate the lower bound, so that we need not know details in the neck. Such a trick has been used by the second author of this paper in [18], [19] to prove the existence of extremal functions for the classical Moser-Trudinger inequality on a compact manifold. Another main point of this paper is the delicate constructions of blowing up sequences  $\phi^\epsilon$  in both cases, so that  $\Phi(\phi^\epsilon)$  are strictly less than the lower bound derived before, and consequently we get a contradiction to the assumption that  $u^\epsilon$  blows up, which proves our main theorem.

After submitting the present article we were informed of the existence of the paper [15], where a result similar to our one is established. As a matter of fact, Jost, Lin and Wang consider the more general equation

$$-\Delta u_i = 4\pi \sum_{j=1}^2 a_{ij} \left( \frac{h_j \exp(u_j)}{\int_{\Sigma} h_j \exp(u_j)} - 1 \right) \quad \text{for } 1 \leq i \leq 2,$$

where  $a_{11} = a_{22} = 2$  and  $a_{12} = a_{21} = -1$ , and  $h_1, h_2$  are positive smooth functions on  $\Sigma$ . Our equation corresponds to the case where  $h_1 \equiv h_2$  is constant. Our approach to the proof is completely different from theirs, and it appears that the more general case considered by them could also be treated with our method. In addition, there are hopes that our techniques could be used to face other non-linear existence problems.

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**2. Review of known results**

For any  $u = (u_1, u_2) \in H^{1,2}(\Sigma) \times H^{1,2}(\Sigma)$ , we set

$$\begin{aligned} \Phi_\epsilon(u) = & \frac{1}{3} \int_\Sigma (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2 + 3(4\pi - \epsilon)u_1 + 3(4\pi - \epsilon)u_2) dV_g \\ & - (4\pi - \epsilon) \log \int_\Sigma e^{u_1} dV_g - (4\pi - \epsilon) \log \int_\Sigma e^{u_2} dV_g. \end{aligned}$$

It is not difficult to check that

$$\Phi_{(4\pi-\epsilon, 4\pi-\epsilon)}(v) = \Phi_\epsilon(u),$$

if we set  $v_1 = \frac{2u_1+u_2}{3}$  and  $v_2 = \frac{u_1+2u_2}{3}$ .

By Jost-Wang’s result ([16] Corollary 4.6), one sees that  $\Phi_\epsilon$  has a minimizer  $u^\epsilon$  of the functional  $\Phi_\epsilon(u)$ , *i.e.* we can find  $u^\epsilon \in H^{1,2}(\Sigma) \times H^{1,2}(\Sigma)$  such that

$$\Phi_\epsilon(u^\epsilon) = \inf \Phi_\epsilon(u).$$

Without loss of generality, we may assume that

$$\int e^{u_1^\epsilon} dV_g = \int e^{u_2^\epsilon} dV_g = 1.$$

Then we have the following equations:

$$\begin{cases} -\Delta u_1^\epsilon = (8\pi - 2\epsilon)e^{u_1^\epsilon} - (4\pi - \epsilon)e^{u_2^\epsilon} - (4\pi - \epsilon) \\ -\Delta u_2^\epsilon = (8\pi - 2\epsilon)e^{u_2^\epsilon} - (4\pi - \epsilon)e^{u_1^\epsilon} - (4\pi - \epsilon) \end{cases}$$

For  $i = 1, 2$ , let

$$S_i = \{x \in \Sigma : \text{there is a sequence } y^\epsilon \rightarrow x \text{ s.t. } u_i^\epsilon(y^\epsilon) \rightarrow +\infty\}.$$

Jost-Wang [16] (section 5) proved that there will be two possibilities:

**Case 1.**  $S_1 = \{p_1\}$ , and  $S_2 = \{p_2\}$ , where  $p_1, p_2$  are two different points in  $\Sigma$ .

In this case, we set, for  $i = 1, 2$ ,

$$m_i^\epsilon = u_i^\epsilon(x_i^\epsilon) = \max u_i^\epsilon, \quad (r_i^\epsilon)^2 = e^{-m_i^\epsilon}, \quad \bar{u}_i^\epsilon = \int_\Sigma u_i^\epsilon dV_g.$$

Let  $(\Omega_i, x = (x^1, x^2))$  be an isothermal coordinate system around  $p_i$  ( $i = 1, 2$ ), and we assume the metric to be

$$g|_{\Omega_i} = e^{\varphi_i} ((dx^1)^2 + (dx^2)^2)$$

with  $\varphi_i(0) = 0, i = 1, 2$ .

We set, for  $i = 1, 2$ ,  $\Omega_i^\epsilon = \{x \in \mathbb{R}^2 : x_i^\epsilon + r_i^\epsilon x \in \Omega_i\}$ , which expands to the whole  $\mathbb{R}^2$ . In  $\Omega_1^\epsilon$ , we have the equations:

$$-\Delta_0(u_1^\epsilon(x_1^\epsilon + r_1^\epsilon x) - m_1^\epsilon) = e^{-\varphi_1(x_1^\epsilon + r_1^\epsilon x)} \left( (8\pi - 2\epsilon)e^{u_1^\epsilon(x_1^\epsilon + r_1^\epsilon x) - m_1^\epsilon} - (r_1^\epsilon)^2(4\pi - \epsilon)e^{u_2^\epsilon(x_1^\epsilon + r_1^\epsilon x)} - (r_1^\epsilon)^2(4\pi - \epsilon) \right),$$

where  $-\Delta_0 = \frac{\partial^2}{\partial^2 x_1} + \frac{\partial^2}{\partial^2 x^2}$ . Since  $u_2^\epsilon$  are bounded from above in  $\Omega_1^\epsilon$ , it follows from the Harnack inequality and the elliptic estimates that  $u_1^\epsilon$  converges in  $C_{loc}^k(\mathbb{R}^2)$  for any  $k$  to the function  $w$  which satisfies the equation

$$\begin{cases} -\Delta w = 8\pi e^w, & \forall x \in \mathbb{R}^2 \\ w(x) \leq w(0) = 0, & \text{and } \int_{\mathbb{R}^2} e^w dx \leq 1. \end{cases}$$

Hence, by the result in [7], we know that

$$w = -2 \log(1 + \pi|x|^2).$$

In the same way,  $u_2^\epsilon(x_2^\epsilon + r_2^\epsilon x) - m_2^\epsilon$  converges to  $w$ .

Setting  $\bar{u}_i^\epsilon = \int_{\Sigma} u_i^\epsilon dV_g$ , we have the following proposition (see Lemma 5.6, and the proof of Theorem 3.1 in [16]).

**Proposition 2.1.** *We have  $\bar{u}_j^\epsilon \rightarrow -\infty$  for  $j = 1, 2$ . Furthermore, for any  $q \in (1, 2)$ , we have*

$$u_j^\epsilon - \bar{u}_j^\epsilon \text{ converges to } G_j \text{ in } H^{1,q}(\Sigma),$$

where  $G_1$  and  $G_2$  satisfy

$$\begin{cases} -\Delta G_1 = 8\pi \delta_{p_1} - 4\pi \delta_{p_2} - 4\pi, \\ -\Delta G_2 = 8\pi \delta_{p_2} - 4\pi \delta_{p_1} - 4\pi, \\ \int_{\Sigma} G_j dV_g = 0, & \text{for } j = 1, 2 \end{cases}$$

where  $\delta_y$  is the Dirac distribution. Moreover,

$$u_j^\epsilon - \bar{u}_j^\epsilon \text{ converges to } G_j \text{ in } C_{loc}^2(\Sigma \setminus \{p_1, p_2\}).$$

**Remark 2.2.** It is easy to see that, in  $\Omega_1$ ,

$$G_1 = -4 \log r + A_1(p_1) + f_1, \quad \text{and } G_2 = 2 \log r + A_2(p_1) + g_1 \quad (2.1)$$

where  $r^2 = x_1^2 + x_2^2$ ,  $A_i(p_1)$  ( $i = 1, 2$ ) are constants, and  $f_1, g_1$  are smooth functions which are zero at 0. Similarly, in  $\Omega_2$ , we can write

$$G_1 = 2 \log r + A_1(p_2) + f_2, \quad \text{and } G_2 = -4 \log r + A_2(p_2) + g_2 \quad (2.2)$$

where  $A_i(p_1)$  ( $i = 1, 2$ ) are constants, and  $f_2, g_2$  are smooth functions which are zero at 0.

**Case 2.**  $S_1 = \{p\}$ , and  $S_2 = \emptyset$ .

In this case,  $u_2^\epsilon$  are bounded from above. Let  $(\Omega; x)$  be an isothermal coordinate system around  $p$ , similar to the Case 1, we have

$$u_1^\epsilon(x_1^\epsilon + r_1^\epsilon x) - m_1^\epsilon \rightarrow -2 \log(1 + \pi|x|^2).$$

We also have the following proposition (c.f. [16]):

**Proposition 2.3.** *Let  $\bar{u}_1^\epsilon$  be the average of  $u_1^\epsilon$ . We have  $\bar{u}_1^\epsilon \rightarrow -\infty$ . Furthermore, for any  $q \in (1, 2)$ , we have*

$$u_1^\epsilon - \bar{u}_1^\epsilon \text{ converges to } G_1 \text{ in } H^{1,q}(\Sigma),$$

and

$$u_2^\epsilon \text{ converges to } G_2 \text{ in } H^{1,q}(\Sigma),$$

where  $G_1$  and  $G_2$  satisfy

$$\begin{cases} -\Delta G_1 = 8\pi\delta_p - 4\pi e^{G_2} - 4\pi, \\ -\Delta G_2 = 8\pi e^{G_2} - 4\pi\delta_p - 4\pi, \\ \int_\Sigma G_1 dV_g = 0, \quad \int_\Sigma e^{G_2} dV_g = 1, \quad \sup_{x \in \Sigma} G_2 < +\infty \end{cases} \quad (2.3)$$

where  $\delta_y$  is the Dirac distribution. Moreover,

$$u_1^\epsilon - \bar{u}_1^\epsilon \text{ converges to } G_1, \text{ and } u_2^\epsilon \text{ converges to } G_2 \text{ in } C_{loc}^2(\Sigma \setminus \{p\}).$$

Since  $G_2$  is bounded from above, we can deduce from the equation (2.3) that  $G_2 = 2 \log r + h$  in  $\Omega$ , where  $h \in H_{loc}^{2,q}(\Omega)$  for any  $q > 0$ . Then  $e^{G_2} = r^2 e^h \in C_{loc}^1(\Omega)$ , and then  $\Delta_0 h \in C_{loc}^1(\Omega)$ . Therefore, by the standard elliptic estimates,  $G_2 - 2 \log r$  is smooth in  $\Omega$ . So, we can write

$$G_1 = -4 \log r + A_1(p) + f, \quad \text{and} \quad G_2 = 2 \log r + A_2(p) + g \quad (2.4)$$

where  $r^2 = x_1^2 + x_2^2$ ,  $A_i(p)$  ( $i = 1, 2$ ) are constants and  $f, g$  are smooth functions which are zero at 0.

### 3. The lower bound for Case 1

We assume that  $\Omega_1 \cap \Omega_2 = \emptyset$ , and  $B_r(p_1) \subset \Omega_1$ . We set  $v_2^\epsilon = \frac{1}{3}(2u_2^\epsilon + u_1^\epsilon) - \frac{1}{3}(2\bar{u}_2^\epsilon + \bar{u}_1^\epsilon)$ . Then, in  $B_r(p_1)$ , we have

$$\begin{cases} -\Delta v_2^\epsilon = (4\pi - \epsilon)e^{u_2^\epsilon} - (4\pi - \epsilon) \in L^\infty(B_r(p_1)) \\ v_2^\epsilon|_{\partial B_r(p_1)} \rightarrow \frac{1}{3}(2G_2 + G_1). \end{cases}$$

So  $\|v_2^\epsilon\|_{C^1} \leq C$ , where  $C$  is a constant depending only on  $r$ .

By a direct calculation one gets

$$\begin{aligned} \frac{1}{3} \int_{B_\delta(x_1^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g &= \frac{1}{4} \int_{B_\delta(x_k)} (|\nabla u_1^\epsilon|^2 + 3|\nabla v_2^\epsilon|^2) dV_g \\ &= \frac{1}{4} \int_{B_\delta(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g + O(\delta^2). \end{aligned}$$

Recall that  $u_1(x_1^\epsilon + r_1^\epsilon x) - m_1^\epsilon \rightarrow w$  in  $C^k(B_L(0))$ , for any  $k$ , we have

$$\begin{aligned} \frac{1}{4} \int_{B_\delta(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g &= \frac{1}{4} \int_{B_L} |\nabla w|^2 dx \\ &+ \frac{1}{4} \int_{B_\delta(x_1^\epsilon) \setminus B_{Lr_1^\epsilon}(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g + o(1) + O(\delta^2). \end{aligned}$$

Let

$$a_1^\epsilon = \inf_{\partial B_{Lr_1^\epsilon}(x_1^\epsilon)} u_1^\epsilon, \quad b_1^\epsilon = \sup_{\partial B_\delta(x_1^\epsilon)} u_1^\epsilon.$$

We set  $a_1^\epsilon - b_1^\epsilon = m_1^\epsilon - \bar{u}_1^\epsilon + d_1^\epsilon$ . It is clear that, for fixed  $L$  and  $\delta$ ,

$$d_1^\epsilon \rightarrow w(L) - \sup_{\partial B_\delta(p_1)} G_1 \text{ as } \epsilon \rightarrow 0.$$

Let  $f_1^\epsilon = \max\{\min\{u_1^\epsilon, a_1^\epsilon\}, b_1^\epsilon\}$ . We get

$$\begin{aligned} \int_{B_\delta(x_1^\epsilon) \setminus B_{Lr_1^\epsilon}(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g &\geq \int_{B_\delta(x_1^\epsilon) \setminus B_{Lr_1^\epsilon}(x_1^\epsilon)} |\nabla f_1^\epsilon|^2 dV_g \\ &= \int_{B_\delta(x_1^\epsilon) \setminus B_{Lr_1^\epsilon}(x_1^\epsilon)} |\nabla_0 f_1^\epsilon|^2 dx \\ &\geq \inf_{\Psi|_{\partial B_{Lr_1^\epsilon}(0)}=a_1^\epsilon, \Psi|_{\partial B_\delta(0)}=b_1^\epsilon} \int_{B_\delta(0) \setminus B_{Lr_1^\epsilon}(0)} |\nabla_0 \Psi|^2 dx. \end{aligned}$$

Here,  $|\nabla_0 g|^2 = \left| \frac{\partial g}{\partial x_1} \right|^2 + \left| \frac{\partial g}{\partial x_2} \right|^2$ . It is well-known that

$$\inf_{\Psi|_{\partial B_{Lr_1^\epsilon}(0)}=a_1^\epsilon, \Psi|_{\partial B_\delta(0)}=b_1^\epsilon} \int_{B_\delta \setminus B_{Lr_1^\epsilon}} |\nabla_0 \Psi|^2 dx$$

is uniquely attained by the function  $\phi$  which satisfies the equation

$$\begin{cases} -\Delta_0\phi = 0 \\ \phi|_{\partial B_{Lr_1^\epsilon}} = a_1^\epsilon, \phi|_{\partial B_\delta} = b_1^\epsilon. \end{cases}$$

Hence,

$$\phi = \frac{a_1^\epsilon - b_1^\epsilon}{-\log Lr_1^\epsilon + \log \delta} \log r + \frac{a_1^\epsilon \log \delta - b_1^\epsilon \log Lr_1^\epsilon}{-\log Lr_1^\epsilon + \log \delta},$$

and then

$$\int_{B_\delta(0) \setminus B_{Lr_1^\epsilon}(0)} |\nabla_0\phi|^2 dx = \frac{4\pi(a_1^\epsilon - b_1^\epsilon)^2}{-\log(Lr_1^\epsilon)^2 + \log \delta^2}.$$

Therefore, we have

$$\int_{B_\delta(x_1^\epsilon) \setminus B_{Lr_1^\epsilon}(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g \geq \frac{4\pi(m_1^\epsilon - \bar{u}_1^\epsilon + d_1^\epsilon)^2}{-\log L^2 - \log(r_1^\epsilon)^2 + \log \delta^2}.$$

Recalling that  $-\log(r_1^\epsilon)^2 = m_1^\epsilon$ , we get

$$\begin{aligned} \int_{B_\delta(x_1^\epsilon) \setminus B_{Lr_1^\epsilon}(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g &\geq 4\pi \frac{(m_1^\epsilon - \bar{u}_1^\epsilon + d_1^\epsilon)^2}{m_1^\epsilon} \left(1 - \frac{\log L^2 - \log \delta^2}{m_1^\epsilon}\right)^{-1} \\ &\geq 4\pi \frac{(m_1^\epsilon - \bar{u}_1^\epsilon + d_1^\epsilon)^2}{m_1^\epsilon} \left(1 + \frac{\log L^2 - \log \delta^2}{m_1^\epsilon} + \frac{A}{(m_1^\epsilon)^2}\right) \\ &\geq 4\pi \frac{(m_1^\epsilon - \bar{u}_1^\epsilon)^2}{m_1^\epsilon} + 8\pi d_1^\epsilon \left(1 - \frac{\bar{u}_1^\epsilon}{m_1^\epsilon}\right) \\ &\quad + 4\pi \left(1 - \frac{\bar{u}_1^\epsilon}{m_1^\epsilon}\right)^2 (\log L^2 - \log \delta^2) + \frac{A'\bar{u}_1^\epsilon}{(m_1^\epsilon)^2}, \end{aligned}$$

where  $A$  and  $A'$  are constants which depend only on  $\delta$  and  $L$ .

Then we have

$$\begin{aligned} \frac{1}{3} \int_{B_\delta(x_1^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g &\geq \frac{1}{4} \int_{B_L} |\nabla w|^2 dx \\ + \pi \frac{(m_1^\epsilon - \bar{u}_1^\epsilon)^2}{m_1^\epsilon} + 2\pi d_1^\epsilon \left(1 - \frac{\bar{u}_1^\epsilon}{m_1^\epsilon}\right) + \pi \left(1 - \frac{\bar{u}_1^\epsilon}{m_1^\epsilon}\right)^2 (\log L^2 - \log \delta^2) \\ + \frac{A'(\delta, L)\bar{u}_1^\epsilon}{(m_1^\epsilon)^2} + o(1) + O(\delta^2). \end{aligned}$$



Similarly, we have

$$\begin{aligned} & \frac{1}{3} \int_{B_\delta(x_2^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g \\ & \geq \frac{1}{4} \int_{B_L} |\nabla w|^2 dx + \pi \frac{(m_2^\epsilon - \bar{u}_2^\epsilon)^2}{m_2^\epsilon} + 2\pi d_1^\epsilon \left(1 - \frac{\bar{u}_2^\epsilon}{m_2^\epsilon}\right) \\ & \quad + \pi \left(1 - \frac{\bar{u}_2^\epsilon}{m_1^\epsilon}\right)^2 (\log L^2 - \log \delta^2) + \frac{A' \bar{u}_2^\epsilon}{(m_2^\epsilon)^2} + o(1) + O(\delta^2). \end{aligned}$$

It follows that

$$\begin{aligned} & \frac{1}{3} \int_{B_\delta(x_1^\epsilon) \cup B_\delta(x_2^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g + (4\pi - \epsilon) \bar{u}_1^\epsilon + (4\pi - \epsilon) \bar{u}_2^\epsilon \\ & \geq \frac{1}{3} \int_{B_\delta(x_1^\epsilon) \cup B_\delta(x_2^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g + 4\pi \bar{u}_1^\epsilon + 4\pi \bar{u}_2^\epsilon \\ & \geq \frac{1}{2} \int_{B_L} |\nabla w|^2 dx \\ & \quad + \sum_{i=1,2} \left( \pi \frac{(m_i^\epsilon + \bar{u}_i^\epsilon)^2}{m_i^\epsilon} + 2\pi d_i^\epsilon \left(1 - \frac{\bar{u}_i^\epsilon}{m_i^\epsilon}\right) + \pi \left(1 - \frac{\bar{u}_2^\epsilon}{m_1^\epsilon}\right)^2 (\log L^2 - \log \delta^2) \right) \\ & \quad + \sum_{i=1,2} \frac{A' \bar{u}_i^\epsilon}{(m_i^\epsilon)^2} + o(1) + O(\delta^2) \\ & \geq \frac{1}{2} \int_{B_L} |\nabla w|^2 dx \\ & \quad + \sum_{i=1,2} \left( \pi m_i^\epsilon \left(1 + \frac{\bar{u}_i^\epsilon}{m_i^\epsilon}\right)^2 + 2\pi d_i^\epsilon \left(1 - \frac{\bar{u}_i^\epsilon}{m_i^\epsilon}\right) + \pi \left(1 - \frac{\bar{u}_2^\epsilon}{m_1^\epsilon}\right)^2 (\log L^2 - \log \delta^2) \right) \\ & \quad + \sum_{i=1,2} \frac{A' \bar{u}_i^\epsilon}{(m_i^\epsilon)^2} + o(1) + O(\delta^2). \end{aligned}$$

We now set  $s_i^\epsilon = 1 + \frac{\bar{u}_i^\epsilon}{m_i^\epsilon}$ . Then, for fixed  $L, \delta$ , we have

$$\begin{aligned} & \frac{1}{3} \int_{\Sigma} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g + (4\pi - \epsilon) \bar{u}_1^\epsilon + (4\pi - \epsilon) \bar{u}_2^\epsilon \\ & \geq \sum_i m_i^\epsilon \left( s_i^\epsilon + O\left(\frac{1}{m_i^\epsilon}\right) \right)^2 + C. \end{aligned}$$

Since  $\Phi_\epsilon(u_\epsilon) \leq C$ , we see that

$$|s_i^\epsilon| = O\left(\frac{1}{m_i^\epsilon}\right).$$

Hence for both  $i = 1, 2$ ,  $s_i^\epsilon \rightarrow 0$  as  $\epsilon \rightarrow 0$ . So,

$$\begin{aligned} & \frac{1}{3} \int_{B_\delta(x_1^\epsilon) \cup B_\delta(x_2^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g + (4\pi - \epsilon) \bar{u}_1^\epsilon + (4\pi - \epsilon) \bar{u}_2^\epsilon \\ & \geq \frac{1}{2} \int_{B_L} |\nabla w|^2 dx + 4\pi d_1^\epsilon + 4\pi d_2^\epsilon + 8\pi(\log L^2 - \log \delta^2) + o(1) + O(\delta^2) \\ & = \frac{1}{2} \int_{B_L} |\nabla w|^2 dx + 8\pi w(L) + 8\pi(\log L^2 - \log \delta^2) \\ & \quad - 4\pi \sup_{\partial B_\delta(p_1)} G_1 - 4\pi \sup_{\partial B_\delta(p_2)} G_2 + o(1) + O(\delta^2). \end{aligned} \tag{3.1}$$

By a direct calculation, we obtain

$$\int_{B_L} |\nabla w|^2 dx = 16\pi \log(1 + \pi L^2) - \frac{16\pi^2 L^2}{1 + \pi L^2}. \tag{3.2}$$

Moreover, by (2.1) and (2.2), we have

$$\begin{aligned} & \frac{1}{3} \int_{B_\delta^c(x_1^\epsilon) \cap B_\delta^c(x_2^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g \\ & = \frac{1}{3} \int_{B_\delta^c(x_1^\epsilon) \cap B_\delta^c(x_2^\epsilon)} (|\nabla G_1|^2 + |\nabla G_2|^2 + \nabla G_1 \nabla G_2) dV_g + o(1) \\ & = -\frac{1}{3} \sum_{i=1,2} \int_{\partial B_\delta(p_i)} \left( G_1 \frac{\partial G_1}{\partial n} + G_2 \frac{\partial G_2}{\partial n} + \frac{G_1 \frac{\partial G_2}{\partial n} + G_2 \frac{\partial G_1}{\partial n}}{2} \right) dS_g + o(1) \\ & \quad + \int_{B_\delta(p_1) + B_\delta(p_2)} 2\pi(G_1 + G_2) dV_g + o(1) \\ & = -\frac{1}{3} \sum_{i=1,2} \int_0^{2\pi} \left( G_1 \frac{\partial G_1}{\partial r} + G_2 \frac{\partial G_2}{\partial r} + \frac{G_1 \frac{\partial G_2}{\partial r} + G_2 \frac{\partial G_1}{\partial r}}{2} \right) r d\theta|_{r=\delta} + o(1) \\ & \quad + \int_{B_\delta(p_1) + B_\delta(p_2)} 2\pi(G_1 + G_2) dV_g + o(1) \\ & = -16\pi \log \delta - 2\pi A_1(p_1) - 2\pi A_2(p_2) + o(1) + O(\delta \log \delta). \end{aligned} \tag{3.3}$$

In the end, (3.1), (3.2) and (3.3) imply that

$$\inf \Phi_0(u) \geq -8\pi \log \pi - 8\pi - 2\pi(A_1(p_1) + A_2(p_2)).$$

**4. Lower bound for Case 2**

In this case we set  $v_2^\epsilon = \frac{1}{3}(2u_2^\epsilon + u_1^\epsilon) - \frac{1}{3}(2\bar{u}_2^\epsilon + \bar{u}_1^\epsilon)$ . Then we have

$$\begin{cases} -\Delta v_2^\epsilon = (4\pi - \epsilon)e^{u_2^\epsilon} - (4\pi - \epsilon) \\ \int v_2^\epsilon = 0 \end{cases}$$

By the standard elliptic estimates,  $\|v_2\|_{C^1(M)} < C$ .

Similarly to Case 1, we have

$$\frac{1}{3} \int_{B_\delta(x_1^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g = \frac{1}{4} \int_{B_\delta(x_1^\epsilon)} |\nabla u_1^\epsilon|^2 dV_g + O(\delta^2),$$

and

$$\begin{aligned} & \frac{1}{4} \int_{B_\delta(x_1^\epsilon)} |\nabla u_1|^2 dV_g + (4\pi - \epsilon)\bar{u}_1^\epsilon \geq \frac{1}{4} \int_{B_L} |\nabla w|^2 dx \\ & + \left( \pi \frac{(m_1^\epsilon + \bar{u}_1^\epsilon)^2}{m_1^\epsilon} + 2\pi d_1^\epsilon \left( 1 - \frac{\bar{u}_1^\epsilon}{m_1^\epsilon} \right) + \pi \left( 1 - \frac{\bar{u}_1^\epsilon}{m_1^\epsilon} \right)^2 (\log L^2 - \log \delta^2) \right) \\ & + \frac{A'\bar{u}_1^\epsilon}{(m_1^\epsilon)^2} + o(1) + O(\delta^2). \end{aligned}$$

By an argument similar to that used in Case 1, we can show that  $\frac{\bar{u}_1^\epsilon}{m_1^\epsilon} \rightarrow -1$ , hence

$$\begin{aligned} & \frac{1}{3} \int_{B_\delta(x_1^\epsilon)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g + (4\pi - \epsilon)\bar{u}_1^\epsilon \\ & \geq \frac{1}{4} \int_{B_L} |\nabla w|^2 dx + 4\pi w(L) \\ & + 4\pi (\log L^2 - \log \delta^2) - 4\pi \sup_{\partial B_\delta(p_1)} G_1 + o(1) + O(\delta^2). \end{aligned}$$

Set

$$G_1 = -4 \log r + A_1(p) + o(x), \quad G_2 = 2 \log r + A_2(p) + o(x).$$

Applying (2.4), we get

$$\begin{aligned} & \frac{1}{3} \int_{B_\delta^c(x_f^c)} (|\nabla u_1|^2 + |\nabla u_2|^2 + \nabla u_1 \nabla u_2) dV_g \\ &= \frac{1}{3} \int_{B_\delta^c(x_f^c)} \left( |\nabla G_1|^2 + |\nabla G_2|^2 + \frac{\nabla G_1 \nabla G_2 + \nabla G_2 \nabla G_1}{2} \right) dV_g + o(1) \\ &= \int_{\partial B_\delta(p)} \left( G_1 \frac{\partial G_1}{\partial n} + G_2 \frac{\partial G_2}{\partial n} + \frac{G_1 \frac{\partial G_2}{\partial n} + G_2 \frac{\partial G_1}{\partial n}}{2} \right) \\ & \quad + 2\pi \int_{B_\delta(p)} (G_1 + G_2) dV_g - 2\pi \int_\Sigma G_2 dV_g + o(1) + O(\delta \log \delta) \\ &= -8\pi \log \delta - 2\pi A_1(p_1) - 2\pi \int_\Sigma G_2 dV_g + o(1) + O(\delta \log \delta). \end{aligned}$$

In the end, we obtain

$$\inf \Phi_0(u) \geq -4\pi \log \pi - 2\pi A_1(p) + 2\pi \int G_2 dV_g.$$

### 5. Test functions for Case 1

In this section we will construct a function  $\phi = (\phi_1, \phi_2) \in H^{1,2}(M) \times H^{1,2}(M)$ , such that

$$\Phi_0(\phi) < -8\pi \log \pi - 8\pi - 2\pi(A_2(p_1) + A_1(p_2)),$$

whenever (1.4) holds. So, under assumption (1.4), Case 1 will not occur.

Let  $(\Omega_i; (x, y))$  be an isothermal coordinate system around  $p_i$  ( $i = 1, 2$ ). We set

$$r(x, y) = \sqrt{x^2 + y^2}, \quad \text{and} \quad B_\delta = \{(x, y) : x^2 + y^2 < \delta^2\}.$$

We assume that near  $p_i$  ( $i = 1, 2$ ), for each  $k = 1, 2$ ,

$$\begin{aligned} G_k &= a_k(p_i) \log r + A_k(p_i) + \lambda_k(p_i)x + \mu_k(p_i)y \\ & \quad + \alpha_k(p_i)x^2 + \beta_k(p_i)y^2 + \gamma_k(p_i)xy + h(x, y) + O(r^4). \end{aligned}$$

We have  $a_1(p_1) = a_2(p_2) = -4$ , and  $a_1(p_2) = a_2(p_1) = 2$ . Moreover, we assume that

$$g|_{\Omega_i} = e^{\varphi_i} (dx^2 + dy^2),$$

and

$$\varphi_i = b_1(p_i)x + b_2(p_i)y + c_1(p_i)x^2 + c_2(p_i)y^2 + c_{12}(p_i)xy + O(r^3).$$

It is well known that

$$\begin{aligned} K(p_i) &= -(c_1(p_i) + c_2(p_i)), \\ |\nabla u|^2 dV_g &= |\nabla u|^2 dx dy, \end{aligned}$$

and

$$\frac{\partial u}{\partial n} dS_g = \frac{\partial u}{\partial r} r d\theta, \quad (S = \partial B_r).$$

For  $\alpha_k$  and  $\beta_k$ , we have the following lemma:

**Lemma 5.1.** *For any  $k, i$ , we have*

$$\alpha_k(p_i) + \beta_k(p_i) = 2\pi.$$

*Proof.* Near  $p_i$  we have

$$2\alpha_k(p_i) + 2\beta_k(p_i) + O(r) = \Delta_0 G_k(x, y) = e^{-\varphi_i} 4\pi. \quad \square$$

We choose

$$\phi_1 = \begin{cases} w\left(\frac{x}{\epsilon}\right) + \lambda_1(p_1)r \cos \theta + \mu_1(p_1)r \sin \theta & (x, y) \in B_{L\epsilon}(p_1) \\ G_1 - \eta_1 H_1^{p_1} + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_1(p_1) & (x, y) \in B_{2L\epsilon} \setminus B_{L\epsilon}(p_1) \\ G_1 - \eta_2 H_1^{p_2} + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_1(p_1) & (x, y) \in B_{2L\epsilon} \setminus B_{L\epsilon}(p_2) \\ \frac{\omega\left(\frac{x}{\epsilon}\right) + 2 \log(1 + \pi L^2)}{2} + \lambda_1(p_2)r \cos \theta + \mu_1(p_2)r \sin \theta \\ \quad + 6 \log L\epsilon - 2 \log(1 + \pi L^2) + A_1(p_2) - A_1(p_1) & (x, y) \in B_{L\epsilon}(p_2) \\ G_1 + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_1(p_1) & \text{otherwise,} \end{cases}$$

and

$$\phi_2 = \begin{cases} w\left(\frac{x}{\epsilon}\right) + \lambda_2(p_2)r \cos \theta + \mu_2(p_2)r \sin \theta & (x, y) \in B_{L\epsilon}(p_2) \\ G_2 - \eta_2 H_2^{p_2} + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_2(p_2) & (x, y) \in B_{2L\epsilon} \setminus B_{L\epsilon}(p_2) \\ G_2 - \eta_1 H_2^{p_1} + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_2(p_2) & (x, y) \in B_{2L\epsilon} \setminus B_{L\epsilon}(p_1) \\ \frac{\omega\left(\frac{x}{\epsilon}\right) + 2 \log(1 + \pi L^2)}{2} + \lambda_2(p_1)r \cos \theta + \mu_2(p_1)r \sin \theta \\ \quad + 6 \log L\epsilon - 2 \log(1 + \pi L^2) + A_2(p_1) - A_2(p_2) & (x, y) \in B_{L\epsilon}(p_1) \\ G_2 + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_2(p_2) & \text{otherwise.} \end{cases}$$

Here,

$$H_k^{p_i} = G_k - a_k(p_i) \log r - A_k(p_i) - \lambda_k(p_i)r \cos \theta - \mu_k(p_i)r \sin \theta,$$

and  $\eta_i$  is a cut-off function which equals 1 in  $B_{L\epsilon}(p_i)$ , equals 0 in  $B_{2L\epsilon}^c(p_i)$ . We may assume that

$$|\nabla \eta_i| \leq \frac{1}{L\epsilon}.$$

Now we compute  $\Phi_0(\phi)$ . Firstly, we compute  $\int_{\Sigma} |\nabla\phi_1|^2 dV_g$  and  $\int_{\Sigma} |\nabla\phi_2|^2 dV_g$ . Let  $\Omega = \Sigma \setminus (B_{L\epsilon}(p_1) \cup B_{L\epsilon}(p_2))$ . Then

$$\begin{aligned} \int_{\Sigma} |\nabla\phi_1|^2 dV_g &= \int_{B_{L\epsilon}(p_1) \cup B_{L\epsilon}(p_2)} |\nabla\phi_1|^2 dx dy + \int_{\Omega} |\nabla G_1|^2 dV_g \\ &\quad - 2 \sum_{i=1,2} \int_{\Sigma} \nabla G_1 \nabla \eta_i H_1^{p_i} dV_g + \sum_{i=1,2} \int_{\Sigma} |\nabla \eta_i H_1^{p_i}|^2 dV_g. \end{aligned}$$

It is clear that we have

$$\int_{B_{L\epsilon}(p_2)} |\nabla\phi_1|^2 dV_g = \frac{1}{4} \int_{B_L} |\nabla w|^2 dx dy + \pi(L\epsilon)^2 (\lambda_1^2(p_2) + \mu_1^2(p_2)),$$

and

$$\int_{B_{L\epsilon}(p_1)} |\nabla\phi_1|^2 dV_g = \int_{B_L} |\nabla w|^2 dx dy + \pi(L\epsilon)^2 (\lambda_1^2(p_1) + \mu_1^2(p_1)).$$

Calculating directly and using the fact that  $\int_0^{2\pi} h d\theta = 0$ , we obtain,

$$\begin{aligned} \int_{\Sigma} \nabla G_1 \nabla \eta_1 H_1^{p_1} dV_g &= - \int_{\partial B_{L\epsilon}(p_1)} \frac{\partial G_1}{\partial n} H_1^{p_1} dS_g - 4\pi \int_{B_{2L\epsilon} \setminus B_{L\epsilon}} \eta_1 H_1^{p_1} dV_g \\ &= - \int_0^{2\pi} \left( -\frac{4}{r} + \lambda_1(p_1) \cos \theta + \mu_1(p_1) \sin \theta + O(r) \right) \\ &\quad \times (\alpha_1(p_1)r^2 \cos^2 \theta + \beta_1(p_1)r^2 \sin^2 \theta + h + O(r^4)) r d\theta \\ &= 4\pi(\alpha_1(p_1) + \beta_1(p_1))(L\epsilon)^2 + O(L\epsilon)^4 \\ &= 8\pi^2(L\epsilon)^2 + O(L\epsilon)^4. \end{aligned}$$

Similarly, we get

$$\int_{\Sigma} \nabla G_1 \nabla \eta_2 H_1^{p_2} dV_g = -4\pi^2(L\epsilon)^2 + O(L\epsilon)^4.$$

It is obvious that

$$\int_{\Sigma} |\nabla \eta_j H_i^{p_j}|^2 dV_g = \int_{B_{2L\epsilon} \setminus B_{L\epsilon}(p_j)} O(r^2) dV_g = O((L\epsilon)^4).$$

Hence

$$\begin{aligned} \int_{\Sigma} |\nabla\phi_1|^2 dV_g &= \frac{5}{4} \int_{B_L} |\nabla w|^2 dx - 8\pi^2(L\epsilon)^2 + \int_{\Omega} |\nabla G_1|^2 dV_g \\ &\quad + \pi(L\epsilon)^2 \sum_{i=1,2} (\lambda_1^2(p_i) + \mu_1^2(p_i)) + O(L\epsilon)^4. \end{aligned}$$

In the same way, we can show that

$$\begin{aligned} \int_{\Sigma} |\nabla\phi_2|^2 dV_g &= \frac{5}{4} \int_{B_L} |\nabla w|^2 dx - 8\pi^2(L\epsilon)^2 + \int_{\Omega} |\nabla G_2|^2 dV_g \\ &\quad + \pi(L\epsilon)^2 \sum_{i=1,2} (\lambda_2^2(p_i) + \mu_2^2(p_i)) + O(L\epsilon)^4. \end{aligned}$$

Next, we compute  $\int_{\Sigma} \nabla\phi_1 \nabla\phi_2 dV_g$ . We have

$$\begin{aligned} \int_{\Sigma} \nabla\phi_1 \nabla\phi_2 dV_g &= \sum_{i=1,2} \int_{B_{L\epsilon}(p_i)} \nabla\phi_1 \nabla\phi_2 dV_g + \int_{\Omega} \nabla G_1 \nabla G_2 dV_g \\ &\quad - \int_{\Sigma} \nabla G_1 \nabla \eta_1 H_2^{p_1} dV_g - \int_{\Sigma} \nabla G_2 \nabla \eta_1 H_1^{p_1} dV_g \\ &\quad - \int_{\Sigma} \nabla G_1 \nabla \eta_2 H_2^{p_2} dV_g - \int_{\Sigma} \nabla G_2 \nabla \eta_2 H_1^{p_2} dV_g \\ &\quad + \sum_{i=1,2} \int_{\Sigma} \nabla \eta_i H_1^{p_i} \nabla \eta_i H_2^{p_i} dV_g \\ &= - \int_{B_L} |\nabla w|^2 dx + \pi(L\epsilon)^2 \sum_{i=1,2} (\lambda_1(p_i)\lambda_2(p_i) + \mu_1(p_i)\mu_2(p_i)) \\ &\quad - 8\pi(L\epsilon)^2 + \int_{\Omega} \nabla G_1 \nabla G_2 dV_g + O((L\epsilon)^4). \end{aligned}$$

Then we calculate  $\int_{\Omega} (|\nabla G_1|^2 + |\nabla G_2|^2 + \nabla G_1 \nabla G_2) dV_g$ . We have

$$\begin{aligned} &\int_{\Omega} (|\nabla G_1|^2 + |\nabla G_2|^2 + \nabla G_1 \nabla G_2) dV_g \\ &= \int_{\Omega} \left( |\nabla G_1|^2 + |\nabla G_2|^2 + \frac{\nabla G_1 \nabla G_2 + \nabla G_2 \nabla G_1}{2} \right) dV_g \\ &= - \int_{\partial B_{L\epsilon}(p_1) + \partial B_{L\epsilon}(p_2)} \left( G_1 \frac{\partial G_1}{\partial n} + G_2 \frac{\partial G_2}{\partial n} + \frac{G_1 \frac{\partial G_2}{\partial n} + G_2 \frac{\partial G_1}{\partial n}}{2} \right) dS_g \\ &\quad + 6\pi \int_{B_{L\epsilon}(p_1) + B_{L\epsilon}(p_2)} (G_1 + G_2) dV_g. \end{aligned}$$

**Lemma 5.2.** *For any  $k, m, i = 1, 2$ , we have*

$$\begin{aligned} \int_{\partial B_r(p_i)} G_k \frac{\partial G_m}{\partial n} dS_g &= 2\pi a_k(p_i) a_m(p_i) \log r + 2\pi^2 a_k(p_i) r^2 \\ &\quad + \pi r^2 (\lambda_k(p_i) \lambda_m(p_i) + \mu_k(p_i) \mu_m(p_i)) \\ &\quad + 2\pi a_k(p_i) A_m(p_i) + 4\pi^2 r^2 A_m(p_i) \\ &\quad + 4\pi^2 r^2 a_m(p_i) \log r + O(r^4 \log r). \end{aligned}$$

*Proof.* Since  $\int_0^{2\pi} h(r, \theta) d\theta = \int_0^{2\pi} \frac{\partial h}{\partial r}(r, \theta) d\theta = 0$ , we have

$$\begin{aligned} \int_{\partial B_r(p_i)} G_k \frac{\partial G_m}{\partial n} dS_g &= \int_0^{2\pi} \left( \frac{a_k(p_i)}{r} + \lambda_k(p_i) \cos \theta + \mu_k(p_i) \sin \theta + 2r\alpha_k(p_i) \cos^2 \theta \right. \\ &\quad + 2r\beta_k(p_i) \sin^2 \theta + 2r\gamma_k(p_i) \sin \theta \cos \theta) (a_m(p_i) \log r \\ &\quad + A_m(p_i) + \lambda_m(p_i)r \cos \theta + \mu_m(p_i)r \sin \theta + r^2\alpha_m(p_i) \cos^2 \theta \\ &\quad \left. + r^2\beta_m(p_i) \sin^2 \theta + r^2\gamma_m(p_i) \sin \theta \cos \theta \right) r d\theta \\ &\quad + O(r^4 \log r) \\ &= 2\pi a_k(p_i) a_m(p_i) \log r + \pi (\alpha_m(p_i) + \beta_m(p_i)) a_k(p_i) r^2 \\ &\quad + \pi r^2 (\lambda_k(p_i) \lambda_m(p_i) + \mu_k(p_i) \mu_m(p_i)) + 2\pi a_k(p_i) A_m(p_i) \\ &\quad + (2\pi r^2 A_m(p_i) + 2\pi r^2 a_m(p_i) \log r) (\alpha_k(p_i) + \beta_k(p_i)) \\ &\quad + O(r^4 \log r). \quad \square \end{aligned}$$

Then

$$\begin{aligned} \int_{\partial B_r(p_1)} G_1 \frac{\partial G_1}{\partial n} dS_g &= 32\pi \log r - 8\pi^2 r^2 + \pi r^2 (\lambda_1^2(p_1) + \mu_1^2(p_1)) \\ &\quad - 8\pi A_1(p_1) + 4\pi^2 r^2 A_1(p_1) - 16\pi^2 r^2 \log r + O(r^4 \log r). \end{aligned}$$

$$\begin{aligned} \int_{\partial B_r(p_1)} G_2 \frac{\partial G_2}{\partial n} dS_g &= 8\pi \log r + 4\pi^2 r^2 + \pi r^2 (\lambda_2^2(p_1) + \mu_2^2(p_1)) \\ &\quad + 4\pi A_2(p_1) + 4\pi^2 r^2 A_2(p_1) + 8\pi^2 r^2 \log r + O(r^4 \log r). \end{aligned}$$

$$\begin{aligned} \int_{\partial B_r(p_1)} G_1 \frac{\partial G_2}{\partial n} dS_g &= -16\pi \log r - 8\pi^2 r^2 + \pi r^2 (\lambda_1(p_1) \lambda_2(p_1) + \mu_1(p_1) \mu_2(p_1)) \\ &\quad - 8\pi A_2(p_1) + 4\pi^2 r^2 A_2(p_1) + 8\pi^2 r^2 \log r + O(r^4 \log r). \end{aligned}$$

$$\begin{aligned} \int_{\partial B_r(p_1)} G_2 \frac{\partial G_1}{\partial n} dS_g &= -16\pi \log r + 4\pi^2 r^2 + \pi r^2 (\lambda_2(p_1) \lambda_1(p_1) + \mu_2(p_1) \mu_1(p_1)) \\ &\quad + 4\pi A_1(p_1) + 4\pi^2 r^2 A_1(p_1) - 16\pi^2 r^2 \log r + O(r^4 \log r). \end{aligned}$$



Hence

$$\begin{aligned} & \int_{\Omega} (|\nabla G_1|^2 + |\nabla G_2|^2) dV_g \\ &= - \left( 80\pi \log L\epsilon - 8\pi^2(L\epsilon)^2 + \pi(L\epsilon)^2 \sum_{i,j=1,2} (\lambda_i^2(j) + \mu_i^2(j)) \right) \\ & \quad - 8\pi A_1(p_1) - 8\pi A_2(p_2) + 4\pi^2(L\epsilon)^2 (A_1(p_1) + A_2(p_2) + A_2(p_1) + A_1(p_2)) \\ & \quad - 16\pi^2(L\epsilon)^2 \log L\epsilon + 4\pi A_2(p_1) + 4\pi A_1(p_2) + 4\pi \int_{\Omega} G_1 dV_g + 4\pi \int_{\Omega} G_2 dV_g \\ & \quad + O((L\epsilon)^4 \log L\epsilon), \end{aligned}$$

and

$$\begin{aligned} & \int_{\Omega} \nabla G_1 \nabla G_2 dV_g \\ &= - \left( -32 \log L\epsilon - 4\pi^2(L\epsilon)^2 + \pi(L\epsilon)^2 \sum_{i \neq j} (\lambda_i(p_j)\lambda_j(p_i) + \mu_i(p_j)\mu_j(p_i)) \right. \\ & \quad - 4\pi A_2(p_1) - 4\pi A_1(p_2) + 2\pi A_1(p_1) + 2\pi A_2(p_2) \\ & \quad \left. + 2\pi^2(L\epsilon)^2 (A_1(p_1) + A_1(p_2) + A_2(p_1) + A_2(p_2)) - 8\pi^2(L\epsilon)^2 \log L\epsilon \right) \\ & \quad + 2\pi \sum_{i=1,2} \int_{B_{L\epsilon}(p_i)} (G_1 + G_2) dV_g + O((L\epsilon)^4 \log L\epsilon). \end{aligned}$$

It is easy to check that

$$\begin{aligned} 6\pi \int_{B_{L\epsilon}(p_1) + B_{L\epsilon}(p_2)} (G_1 + G_2) dV_g &= 6\pi^2(L\epsilon)^2 \left( \sum_{i,j=1,2} A_i(p_j) \right) - 24\pi^2(L\epsilon)^2 \log L\epsilon \\ & \quad + 12\pi^2(L\epsilon)^2 + O((L\epsilon)^4 \log L\epsilon). \end{aligned}$$

So, we get

$$\begin{aligned} \int_{\Sigma} (|\nabla \phi_1|^2 + |\nabla \phi_2|^2 + \nabla \phi_1 \nabla \phi_2) dV_g &= \frac{3}{2} \int_{B_L} |\nabla w|^2 dx dy - 48\pi \log L\epsilon + 6\pi A_1(p_1) \\ & \quad + 6\pi A_2(p_2) + O((L\epsilon)^4 \log L\epsilon). \end{aligned} \tag{5.1}$$

We calculate  $\int_{\Sigma} (\phi_1 + \phi_2) dV_g$ . We have

$$\begin{aligned} \int_{\Sigma} \phi_1 dV_g &= \epsilon^2 \int_{B_L} w e^{\varphi(\epsilon x, \epsilon y)} dx dy - \int_{\Sigma} (\eta_1 H_1^{p_1} + \eta_2 H_1^{p_2}) dV_g \\ &\quad + (4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_1(p_1)) \\ &\quad \times \left(1 - \int_{B_{L\epsilon}(p_1)} dV_g\right) + 2 \log L\epsilon \int_{B_{L\epsilon}(p_2)} dV_g \\ &\quad + A_1(p_2) \int_{B_{L\epsilon}(p_2)} dV_g - \int_{B_{L\epsilon}(p_1) + B_{L\epsilon}(p_2)} G_1 \\ &\quad - \epsilon^2 \int_{B_L} \frac{w + 2 \log(1 + \pi L^2)}{2} dV_g \\ &\quad + \sum_{i=1,2} \int_{B_{L\epsilon}(p_i)} (\lambda_1(p_i)x + \mu_1(p_i)y) dV_g. \end{aligned}$$

Since

$$\begin{aligned} \int_{B_{L\epsilon}(p_1) + B_{L\epsilon}(p_2)} G_1 dV_g &= \int_0^{L\epsilon} (-2 \log r + A_1(p_1) + A_1(p_2)) 2\pi r dr \\ &\quad + O((L\epsilon)^4 \log L\epsilon) \\ &= -2\pi(L\epsilon)^2 \log L\epsilon + \pi(L\epsilon)^2 \\ &\quad + (A_1(p_1) + A_1(p_2))\pi(L\epsilon)^2 + O((L\epsilon)^4 \log L\epsilon), \end{aligned}$$

we have

$$\begin{aligned} \int_{\Sigma} \phi_1 dV_g &= \frac{\epsilon^2}{2} \int_{B_L} w e^{\varphi(\epsilon x, \epsilon y)} dx dy + 4 \log L\epsilon + \pi(L\epsilon)^2 \log(1 + \pi L^2) \\ &\quad - \pi(L\epsilon)^2 - A_1(p_1) - 2 \log(1 + \pi L^2) + O((L\epsilon)^4 \log L\epsilon). \end{aligned}$$

Similarly, we have

$$\begin{aligned} \int_{\Sigma} \phi_2 dV_g &= \frac{\epsilon^2}{2} \int_{B_L} w e^{\varphi(\epsilon x, \epsilon y)} dx dy + 4 \log L\epsilon + \pi(L\epsilon)^2 \log(1 + \pi L^2) \\ &\quad - \pi(L\epsilon)^2 - A_2(p_2) - 2 \log(1 + \pi L^2) + O((L\epsilon)^4 \log L\epsilon). \end{aligned}$$

Moreover, we have

$$\int_{B_L} \omega e^{\varphi(\epsilon x, \epsilon y)} dx dy = 2\pi L^2 - 2 \log(1 + \pi L^2) - 2\pi L^2 \log(1 + \pi L^2) + O(L^2 \epsilon^2 \log L),$$

hence, we get

$$\int_{\Sigma} (\phi_1 + \phi_2) dV_g = -A_1(p_1) - A_2(p_2) + 8 \log L\epsilon - 4 \log(1 + \pi L^2) - 2\epsilon^2 \log(1 + \pi L^2) + O((L\epsilon)^4 \log L\epsilon). \tag{5.2}$$

We denote  $B(p_j) = \frac{(b_1(p_j) + \lambda_1(p_j))^2 + (b_2(p_j) + \lambda_2(p_j))^2}{4}$  and  $M_i = \frac{-\frac{K(p_i)}{2} + B(p_i)}{\pi}$ . Then we have

$$\begin{aligned} & \int_{B_{L\epsilon}(p_1)} e^{\phi_1} dV_g \\ &= \epsilon^2 \int_{B_L} \frac{e^{(b_1(p_1) + \lambda_1(p_1))\epsilon x + (b_2(p_1) + \lambda_2(p_1))\epsilon y + c_1(p_1)\epsilon^2 x^2 + c_2(p_1)\epsilon^2 y^2 + c_{12}\epsilon^2 xy + O((r\epsilon)^3)}}{(1 + \pi r^2)^2} dx dy \\ &= \epsilon^2 \int_0^L \frac{1 + \epsilon^2 \pi M_1 r^2 + O(\epsilon^3 r^3)}{(1 + \pi r^2)^2} 2\pi r dr \\ &= \epsilon^2 (1 - \epsilon^2 M_1) \frac{\pi L^2}{1 + \pi L^2} + \epsilon^4 M_1 \log(1 + \pi L^2) + \epsilon^2 O(\epsilon^3 \log L) \\ &= \epsilon^2 \left( 1 - \frac{1}{1 + \pi L^2} + \epsilon^2 M_1 \log(1 + \pi L^2) + O(\epsilon^2) + O(\epsilon^3 \log L) \right), \end{aligned}$$

and we also have

$$\begin{aligned} & \int_{B_{\delta}(p_1) \setminus B_{L\epsilon}(p_1)} e^{\phi_1} dV_g \\ &= \frac{(L\epsilon)^4}{(1 + \pi L^2)^2} \int_{L\epsilon}^{\delta} e^{-4 \log r + (\lambda_1(p_1) + b_1(p_1))x + (\mu_1(p_1) + b_2(p_1))y} \\ & \quad \times e^{(c_1(p_1) + \alpha_1(p_1))x^2 + (c_2(p_1) + \beta_1(p_1))y^2 + (c_{12}(p_1) + \gamma_1)xy + (1 - \eta_1)H_1^{p_1} + O(r^3)} 2\pi r dr \\ &= \epsilon^2 \left( \frac{\pi L^2}{(1 + \pi L^2)^2} - 2(M_1 + 1)\epsilon^2 \log L\epsilon + O(\epsilon^2) + O\left(\frac{1}{L^4}\right) \right). \end{aligned}$$

Since  $G_1$  is bounded above, outside  $B_{\delta}(p_1)$ , we have

$$\int_{\Sigma \setminus B_{\delta}} e^{\phi_1} = O(\epsilon^4).$$

Noting that  $\frac{\pi L^2}{(1 + \pi L^2)^2} - \frac{1}{1 + \pi L^2} = O\left(\frac{1}{L^4}\right)$ , we get

$$\begin{aligned} \log \int_{\Sigma} e^{\phi_1} dV_g &= \log \epsilon^2 + \epsilon^2 M_1 \log(1 + \pi L^2) - 2\epsilon^2 (M_1 + 1) \log L\epsilon \\ & \quad + O(\epsilon^2) + O\left(\frac{1}{L^4}\right). \end{aligned} \tag{5.3}$$

In the same way, we can get

$$\begin{aligned} \log \int_{\Sigma} e^{\phi_2} dV_g &= \log \epsilon^2 + \epsilon^2 M_2 \log(1 + \pi L^2) - 2\epsilon^2 (M_2 + 1) \log L\epsilon \\ &\quad + O(\epsilon^2) + O\left(\frac{1}{L^4}\right). \end{aligned} \tag{5.4}$$

It follows from (5.1), (5.2), (5.3) and (5.4) that

$$\begin{aligned} \Phi_0(\phi) &= \frac{1}{2} \int_{B_L} |\nabla w|^2 dx dy + 16 \log L\epsilon - 2\pi(A_1(p_1) + A_2(p_2)) \\ &\quad - 16\pi \log(1 + \pi L^2) - 8\pi \log \epsilon^2 - 8\pi \epsilon^2 \log(1 + \pi L^2) \\ &\quad - 4\pi \epsilon^2 \left( (M_1 + M_2) \log(1 + \pi L^2) - 2(M_1 + M_2 + 2) \log L\epsilon \right) \\ &\quad + O\left(\frac{1}{L^4}\right) + O(\epsilon^2) + O((L\epsilon)^4 \log L\epsilon) + O(\epsilon^3 \log L) \\ &= -8\pi \log \frac{1 + \pi L^2}{L^2} - 8\pi \frac{\pi L^2}{1 + \pi L^2} - 2\pi(A_1(p_1) + A_2(p_2)) \\ &\quad - 4\pi \epsilon^2 (M_1 + M_2 + 2) (\log(1 + \pi L^2) - 2 \log L\epsilon) \\ &\quad + O\left(\frac{1}{L^4}\right) + O(\epsilon^2) + O((L\epsilon)^4 \log L\epsilon) + O(\epsilon^3 \log L) \\ &= -8\pi \log \pi - 8\pi - 2\pi(A_1(p_1) + A_2(p_2)) \\ &\quad - 4\pi (M_1 + M_2 + 2) \epsilon^2 (\log(1 + \pi L^2) - 2 \log L\epsilon) \\ &\quad + O\left(\frac{1}{L^4}\right) + O(\epsilon^2) + O((L\epsilon)^4 \log L\epsilon) + O(\epsilon^3 \log L). \end{aligned}$$

Under assumption (1.1) we have  $M_1 + M_2 + 2 > 0$ . Leting  $L^4 \epsilon^2 = \frac{1}{\log(-\log \epsilon)}$ , we get

$$\begin{aligned} \Phi_0(\phi) &= -8\pi \log \pi - 8\pi - 2\pi(A_1(p_1) + A_2(p_2)) \\ &\quad - 4\pi (M_1 + M_2 + 2) \epsilon^2 (-\log \epsilon^2) + o(\epsilon^2 (-\log \epsilon^2)). \end{aligned}$$

Then for sufficiently small  $\epsilon$  we have

$$\Phi_0(\phi) < -8\pi \log \pi - 8\pi - 2\pi(A_1(p_1) + A_2(p_2)).$$

This proves our claim.

### 6. Test functions for Case 2

Assuming that (1.4) holds on  $\Sigma$ , we will construct a function  $\phi = (\phi_1, \phi_2) \in H^{1,2}(M) \times H^{1,2}(M)$ , such that

$$\Phi_0(\phi) < -4\pi \log \pi - 2\pi A_1(p) + 2\pi \int G_2 dV_g.$$

Let  $(\Omega; (x, y))$  be an isothermal coordinate system around  $p$ . We assume that near  $p$

$$G_k = a_k \log r + A_k(p) + \lambda_k x + \mu_k y + \alpha_k x^2 + \beta_k y^2 + \gamma_k xy + h_k(x, y) + O(r^4).$$

We have  $a_1(p) = -4$ , and  $a_2(p_1) = 2$ . Moreover we assume that

$$g|_{\Omega} = e^{\varphi}(dx^2 + dy^2),$$

and

$$\varphi = b_1x + b_2y + c_1x^2 + c_2y^2 + c_{12}xy + O(r^3).$$

Similarly to Case 1, there hold

$$\alpha_k + \beta_k = 2\pi, \quad i = 1, 2.$$

We choose

$$\phi_1 = \begin{cases} w\left(\frac{x}{\epsilon}\right) + \lambda_1 r \cos \theta + \mu_1 r \sin \theta & x \in B_{L\epsilon}(p) \\ G_1 - \eta H_1 + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_1(p) & x \in B_{2L\epsilon} \setminus B_{L\epsilon}(p) \\ G_1 + 4 \log L\epsilon - 2 \log(1 + \pi L^2) - A_1(p_1) & \text{otherwise,} \end{cases}$$

and

$$\phi_2 = \begin{cases} -\frac{w\left(\frac{x}{\epsilon}\right) + 2 \log(1 + \pi L^2)}{2} + 2 \log L\epsilon \\ \quad + \lambda_2 r \cos \theta + \mu_2 r \sin \theta + A_2(p) & x \in B_{L\epsilon}(p) \\ G_2 - \eta H_2 & x \in B_{2L\epsilon} \setminus B_{L\epsilon}(p) \\ G_2 & \text{otherwise.} \end{cases}$$

Here

$$H_k = G_k - a_k \log r - A_k + \lambda_k r \cos \theta + \mu_k r \sin \theta$$

and  $\eta_i$  is a cut-off function which equals 1 in  $B_{L\epsilon}(p)$ , equals 0 in  $B_{2L\epsilon}^c(p)$ .

Let  $\Omega = \Sigma \setminus B_{L\epsilon}(p)$ . By an argument similar that used in Section 5, we can derive that

$$\begin{aligned} \int_{\Sigma} |\nabla \phi_1|^2 dV_g &= \int_{B_{L\epsilon}(p)} |\nabla \phi_1|^2 dx dy + \int_{\Omega} |\nabla G_1|^2 dV_g \\ &\quad - 2 \int_{\Sigma} \nabla G_1 \nabla \eta H_1 dV_g + \int_{\Sigma} |\nabla \eta H_1|^2 dV_g \\ &= \int_{B_L} |\nabla w|^2 dx dy - 16\pi(L\epsilon)^2 + \pi(L\epsilon)^2(\lambda_1^2 + \mu_1^2) + O((L\epsilon)^4), \end{aligned}$$

$$\begin{aligned} \int_{\Sigma} |\nabla\phi_2|^2 dV_g &= \int_{B_{L\epsilon}(p)} |\nabla\phi_1|^2 dx dy + \int_{\Omega} |\nabla G_2|^2 dV_g \\ &\quad - 2 \int_{\Sigma} \nabla G_2 \nabla \eta_2 H_2 dV_g + \int_{\Sigma} |\nabla \eta H_2|^2 dV_g \\ &= \frac{1}{4} \int_{B_L} |\nabla w|^2 dx dy + 8\pi(L\epsilon)^2 + \pi(L\epsilon)^2(\lambda_2^2 + \mu_2^2) + O((L\epsilon)^4), \end{aligned}$$

and

$$\begin{aligned} \int_{\Sigma} \nabla\phi_1 \nabla\phi_2 dV_g &= \int_{\Omega} \nabla G_1 \nabla G_2 dV_g + \int_{B_{L\epsilon}(p)} \nabla\phi_1 \nabla\phi_2 dV_g \\ &\quad - \int_{\Sigma} \nabla G_1 \nabla \eta H_2 dV_g - \int_{\Sigma} \nabla G_2 \nabla \eta H_1 dV_g + \int_{\Sigma} \nabla \eta H_1 \nabla \eta H_2 dV_g \\ &= -\frac{1}{2} \int_{B_L} |\nabla w|^2 dx dy + \pi(L\epsilon)^2(\lambda_1\lambda_2 + \mu_1\mu_2) \\ &\quad - 4\pi(L\epsilon)^2 + \int_{\Omega} \nabla G_1 \nabla G_2 dV_g + O((L\epsilon)^4). \end{aligned}$$

Note that

$$\begin{aligned} &\int_{\Omega} (|\nabla G_1|^2 + |\nabla G_2|^2 + \nabla G_1 \nabla G_2) dV_g \\ &= \int_{\Omega} \left( |\nabla G_1|^2 + |\nabla G_2|^2 + \frac{\nabla G_1 \nabla G_2 + \nabla G_2 \nabla G_1}{2} \right) dV_g \\ &= -\int_{\partial B_{L\epsilon}(p)} \left( G_1 \frac{\partial G_1}{\partial n} + G_2 \frac{\partial G_2}{\partial n} + \frac{G_1 \frac{\partial G_2}{\partial n} + G_2 \frac{\partial G_1}{\partial n}}{2} \right) dS_g \\ &\quad + 6\pi \int_{B_{L\epsilon}(p)} (G_1 + G_2) - 6\pi \int_{\Sigma} G_2 dV_g. \end{aligned}$$

Applying Lemma 5.2, we get

$$\begin{aligned} \int_{\partial B_r(p)} G_1 \frac{\partial G_1}{\partial n} dS_g &= 32\pi \log r - 8\pi^2 r^2 + \pi r^2(\lambda_1^2 + \mu_1^2) \\ &\quad - 8\pi A_1(p) + 4\pi^2 r^2 A_1(p) - 16\pi^2 r^2 \log r + O(r^4 \log r), \end{aligned}$$

$$\begin{aligned} \int_{\partial B_r(p)} G_2 \frac{\partial G_2}{\partial n} dS_g &= 8\pi \log r + 4\pi^2 r^2 + \pi r^2(\lambda_2^2 + \mu_2^2) \\ &\quad + 4\pi A_2(p) + 4\pi^2 r^2 A_2(p) + 8\pi^2 r^2 \log r + O(r^4 \log r), \end{aligned}$$

$$\begin{aligned} \int_{\partial B_r(p)} G_1 \frac{\partial G_2}{\partial n} dS_g &= -16\pi \log r - 8\pi^2 r^2 + \pi r^2(\lambda_1\lambda_2 + \mu_1\mu_2) \\ &\quad - 8\pi A_2(p) + 4\pi^2 r^2 A_2(p) + 8\pi^2 r^2 \log r + O(r^4 \log r), \end{aligned}$$

$$\int_{\partial B_r(p)} G_2 \frac{\partial G_1}{\partial n} dS_g = -16\pi \log r + 4\pi^2 r^2 + \pi r^2(\lambda_2 \lambda_1 + \mu_2 \mu_1) + 4\pi A_1(p) + 4\pi^2 r^2 A_1(p) - 16\pi^2 r^2 \log r + O(r^4 \log r).$$

Noticing that

$$6\pi \int_{B_{L\epsilon}(p)} (G_1 + G_2) dV_g = 6\pi^2 (L\epsilon)^2 (A_1(p) + A_2(p)) - 12\pi^2 (L\epsilon)^2 \log L\epsilon + 6\pi^2 (L\epsilon)^2 + O((L\epsilon)^4 \log L\epsilon),$$

we get

$$\begin{aligned} & \int_{\Sigma} (|\nabla \phi_1|^2 + |\nabla \phi_2|^2 + \nabla \phi_1 \nabla \phi_2) dV_g \\ &= \frac{3}{4} \int_{B_L} |\nabla w|^2 dx dy - 24\pi \log L\epsilon \\ & \quad - 6\pi A_1(p_1) - 6\pi \int G_2 dV_g + O((L\epsilon)^4 \log L\epsilon). \end{aligned} \tag{6.1}$$

We have

$$\begin{aligned} \int_{\Sigma} \phi_1 dV_g &= \epsilon^2 \int_{B_L} w dV_g - \int_{\Sigma} \eta H_1 dV_g + (4 \log L\epsilon - 2 \log(1 + \pi L^2) \\ & \quad - A_1(p))(1 - \int_{B_{L\epsilon}(p)} dV_g) + \int_{B_{L\epsilon}(p)} (\lambda_1 x + \mu_1 y) dV_g \\ & \quad - \int_{B_{L\epsilon}(p)} G_1 dV_g + O((L\epsilon)^4 \log L\epsilon) \\ &= \epsilon^2 \int_{B_L} w e^{\varphi(\epsilon x, \epsilon y)} dx dy + 4 \log L\epsilon + 2\pi (L\epsilon)^2 \log(1 + \pi L^2) \\ & \quad - 2\pi (L\epsilon)^2 - A_1(p) - 2 \log(1 + \pi L^2) + O((L\epsilon)^4 \log L\epsilon). \end{aligned}$$

Since

$$\begin{aligned} \int_{B_{L\epsilon}(p)} G_2 dV_g &= \int_0^{L\epsilon} (2 \log r + A_2(p)) 2\pi L\epsilon dr + O((L\epsilon)^4 \log L\epsilon) \\ &= 2\pi r^2 \log r - \pi r^2 + (A_1(p)\pi r^2 + O((L\epsilon)^4 \log L\epsilon)), \end{aligned}$$

we can see that

$$\begin{aligned} \int_{\Sigma} \phi_2 dV_g &= \int_{\Sigma} G_2 dV_g - \int_{B_{L\epsilon}(p)} G_2 dV_g \\ &\quad - \int_{\Sigma} \eta\beta_2 dV_g + (2 \log L\epsilon + A_1(p)) \int_{B_{L\epsilon}} dV_g \\ &\quad - \epsilon^2 \int_{B_L} \frac{w + 2 \log(1 + \pi L^2)}{2} e^{\varphi(\epsilon x, \epsilon y)} dx dy + O((L\epsilon)^4 \log L\epsilon) \\ &= -\frac{\epsilon^2}{2} \int_{B_L} w e^{\varphi(\epsilon x, \epsilon y)} dx dy \\ &\quad - \pi(L\epsilon)^2 \log(1 + \pi L^2) + \pi(L\epsilon)^2 + O((L\epsilon)^4 \log L\epsilon). \end{aligned}$$

Hence,

$$\begin{aligned} \int (\phi_1 + \phi_2) dV_g &= -A_1(p) + 4 \log L\epsilon - \epsilon^2 \log(1 + \pi L^2) \\ &\quad - 2 \log(1 + \pi L^2) + O((L\epsilon)^4 \log L\epsilon). \end{aligned} \tag{6.2}$$

Setting  $B(p) = \frac{(b_1 + \lambda_1)^2 + (b_2 + \lambda_2)^2}{4}$  and  $M = \frac{-\frac{K(p)}{2} + B(p)}{\pi}$ , we have

$$\begin{aligned} \log \int_{\Sigma} e^{\phi_1} dV_g &= \log \epsilon^2 + \epsilon^2 M \log(1 + \pi L^2) - 2\epsilon^2(M + 1) \log L\epsilon \\ &\quad + O(\epsilon^2) + O((L\epsilon)^3 \log L) + O\left(\frac{1}{L^4}\right). \end{aligned} \tag{6.3}$$

It is easy to see that

$$\int_{B_{2L\epsilon}(0)} e^{\phi_2} dV_g = O((L\epsilon)^4),$$

and

$$\int_{B_{2L\epsilon}(0)} e^{G_2} dV_g = O((L\epsilon)^4).$$

Since  $\int e^{G_2} = 1$ , we get

$$\log \int_{\Sigma} e^{\phi_2} = \log(1 - O((L\epsilon)^4)) = O((L\epsilon)^4). \tag{6.4}$$

In the end, we can deduce from (6.1), (6.2), (6.3) and (6.4) that

$$\begin{aligned} \Phi_0(\phi) &= -4\pi - 4\pi \log \pi + 2 \int G_2 dV_g - \epsilon^2(\log(1 + \pi L^2) - 2 \log L\epsilon)(1 + M) \\ &\quad + O\left(\frac{1}{L^4}\right) + O(\epsilon^3 \log L) + O((L\epsilon)^4 \log L\epsilon) + O(\epsilon^2). \end{aligned}$$



Let  $L^4\epsilon^2 = \frac{1}{\log(-\log \epsilon)}$ . Then for  $\epsilon$  sufficiently small we have

$$\Phi_0(\phi) < -4\pi - 4\pi \log \pi + 2 \int G_2 dV_g.$$

This proves our claim.

Therefore, if  $\Sigma$  satisfies the condition

$$\max_{p \in \Sigma} K(p) < 2\pi,$$

we can see that  $u^\epsilon$  converges to  $u^0 = (u_1^0, u_2^0)$  in  $H_2 := H^{1,2}(\Sigma) \times H^{1,2}(\Sigma)$ , hence it is clear that  $\Phi(u^0) = \inf_{u \in H_2} \Phi(u)$ , that is,  $u^0$  is a minimizer of  $\Phi_0 = \Phi$ . This completes the proof of the main theorem.

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