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# Qualitative properties of solutions to semilinear elliptic equations from the gravitational Maxwell Gauged $O(3)$ Sigma model

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## Abstract

This article is devoted to the study of the following semilinear equation with measure data which originates in the gravitational Maxwell gauged  $O(3)$  sigma model,

$$(E) \quad -\Delta u + A_0 \left( \prod_{j=1}^k |x - p_j|^{2n_j} \right)^{-a} \frac{e^u}{(1 + e^u)^{1+a}} = 4\pi \sum_{j=1}^k n_j \delta_{p_j} - 4\pi \sum_{j=1}^l m_j \delta_{q_j} \quad \text{in } \mathbb{R}^2,$$

where  $\{\delta_{p_j}\}_{j=1}^k$  (resp.  $\{\delta_{q_j}\}_{j=1}^l$ ) are Dirac masses concentrated at the points  $\{p_j\}_{j=1}^k$ , (resp.  $\{q_j\}_{j=1}^l$ ),  $n_j$  and  $m_j$  are positive integers and  $a \geq 0$ . We set  $N = \sum_{j=1}^k n_j$  and  $M = \sum_{j=1}^l m_j$ .

In previous works [10, 31], some qualitative properties of solutions of (E) with  $a = 0$  have been established. Our aim in this article is to study the more general case where  $a > 0$ . The additional difficulty of this case comes from the fact that the nonlinearity is no longer monotone and we cannot construct directly supersolutions and subsolutions anymore. Instead we develop a new and self-contained approach which enables us to emphasize the role played by the gravitation in gauged  $O(3)$  sigma model. Without the gravitational term, i.e.  $a = 0$ , problem (E) has a layer's structure of solutions  $\{u_\beta\}_{\beta \in (-2(N-M), -2]}$ , where  $u_\beta$  is the unique non-topological solution such that  $u_\beta = \beta \ln |x| + O(1)$  for  $-2(N-M) < \beta < -2$  and  $u_{-2} = -2 \ln |x| - 2 \ln \ln |x| + O(1)$  at infinity respectively. On the contrary, when  $a > 0$ , the set of solutions to problem (E) has a much richer structure: besides the topological solutions, there exists a sequence of non-topological solutions in type I, i.e. such that  $u$  tends to  $-\infty$  at infinity, of non-topological solutions in type II, which tend to  $\infty$  at infinity. The existence of these types of solutions depends on the values of the parameters  $N$ ,  $M$ ,  $\beta$  and on the gravitational interaction associated to  $a$ .

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## 1 Introduction

In this paper our goal is to classify the solutions of the following equation with measure data

$$-\Delta u + A_0 \left( \prod_{j=1}^k |x - p_j|^{2n_j} \right)^{-a} \frac{e^u}{(1 + e^u)^{1+a}} = 4\pi \sum_{j=1}^k n_j \delta_{p_j} - 4\pi \sum_{j=1}^l m_j \delta_{q_j} \quad \text{in } \mathbb{R}^2, \quad (1.1)$$

where  $\{\delta_{p_j}\}_{j=1}^k$  (resp.  $\{\delta_{q_j}\}_{j=1}^l$ ) are Dirac masses concentrated at the points  $\{p_j\}_{j=1}^k$ , (resp.  $\{q_j\}_{j=1}^l$ ),  $p_j \neq p_{j'}$  for  $j \neq j'$ , the related coefficients  $n_j$  and  $m_j$  are positive integers,  $A_0 > 0$  is a given constant,  $a = 16\pi G$  with  $G$  being the Newton's gravitational constant (or more precisely a dimensionless rescaling factor of the gravitational constant [30]) which is of the order of  $10^{-30}$ , meaning that physically speaking the exponent  $a$  is very small. Set

$$\mathbf{P}(x) = A_0 \left( \prod_{j=1}^k |x - p_j|^{2n_j} \right)^{-a}. \quad (1.2)$$

Since

$$2^{-1-a} \min\{e^u, e^{-au}\} \leq \frac{e^u}{(1 + e^u)^{1+a}} \leq \min\{e^u, e^{-au}\}, \quad (1.3)$$

we define the notion of weak solution as follows:

**Definition 1.1** A function  $u \in L^1_{loc}(\mathbb{R}^2)$  such that  $\mathbf{P} \min\{e^u, e^{-au}\} \in L^1_{loc}(\mathbb{R}^2)$  is called a weak solution of (E), if for any  $\xi \in C^\infty_c(\mathbb{R}^2)$ ,

$$\int_{\mathbb{R}^2} u(-\Delta)\xi \, dx + \int_{\mathbb{R}^2} \mathbf{P} \frac{e^u}{(1+e^u)^{1+a}} \xi \, dx = 4\pi \sum_{j=1}^k n_j \xi(p_j) - 4\pi \sum_{j=1}^l m_j \xi(q_j).$$

This means that the following equation holds in the sense of distributions in  $\mathbb{R}^2$

$$-\Delta u + \mathbf{P} \frac{e^u}{(1+e^u)^{1+a}} = 4\pi \sum_{j=1}^k n_j \delta_{p_j} - 4\pi \sum_{j=1}^l m_j \delta_{q_j}. \quad (1.4)$$

If we denote by  $\Sigma := \{p_1, \dots, p_k, q_1, \dots, q_l\}$  the set of supports of the measures, and since the nonlinearity in (1.4) is locally bounded in  $\mathbb{R}^2 \setminus \Sigma$ , a weak solution of (1.4) is a strong solution of

$$-\Delta u + \mathbf{P} \frac{e^u}{(1+e^u)^{1+a}} = 0 \quad \text{in } \mathbb{R}^2 \setminus \Sigma. \quad (1.5)$$

The nonlinear term is not monotone, actually the function  $u \mapsto \frac{e^u}{(1+e^u)^{1+a}}$  is increasing on  $(-\infty, -\ln a)$ , and decreasing on  $(-\ln a, \infty)$ . This makes the problem much more difficult to study than the case where  $a = 0$ .

## 1.1 Physical models and related equations

Equation (1.1) comes from the Maxwell gauged  $O(3)$  sigma model. When  $a = 0$ , it governs the self-dual  $O(3)$  gauged sigma model developed from Heisenberg ferromagnet, see references [1, 2, 24, 27, 31]. When the sigma model for Heisenberg ferromagnet with magnetic field is two-dimensional, it can be expressed by a local  $U(1)$ -invariant action density:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} D_\mu \phi \overline{D^\mu \phi} - \frac{1}{2} (1 - \vec{n} \cdot \phi)^2,$$

where  $\vec{n} = (0, 0, 1)$ ,  $\phi = (\phi_1, \phi_2, \phi_3)$  is a spin vector defined over the  $(2+1)$ -dimensional Minkowski spacetime  $\mathbb{R}^{2,1}$ , with value in the unit sphere  $\mathbb{S}^2$ , i.e.  $|\phi| = 1$ ,  $D_\mu$  are gauge-covariant derivatives on  $\phi$ , defined by

$$D_\mu \phi = \partial_\mu \phi + A_\mu (\vec{n} \times \phi) \quad \text{where } \mu = 0, 1, 2$$

and  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$  is the electromagnetic curvature induced from the 3-vector connection  $A_\nu$ ,  $\nu = 0, 1, 2$  as detailed in [33, p. 441]. When considering the static situation, i.e. the time gauge  $A_0 = 0$ , the functional of total energy can be expressed by the following expressions

$$\begin{aligned} E(\phi, A) &= \frac{1}{2} \int_{\mathbb{R}^2} ((D_1 \phi)^2 + (D_2 \phi)^2 + (1 - \vec{n} \cdot \phi)^2 + F_{12}^2) \, dx \\ &= 4\pi |\deg(\phi)| + \frac{1}{2} \int_{\mathbb{R}^2} ((D_1 \phi \pm \phi \times D_2 \phi)^2 + (F_{12} \mp (1 - \vec{n} \cdot \phi))^2) \, dx, \end{aligned}$$

where  $\deg(\phi)$  denotes the Brouwer's degree of  $\phi$ . The related Bogomol'nyi equation is obtained by using the stereographic projection from the south pole  $\mathcal{S} = (0, 0, -1)$  of  $\mathbb{S}^2 \setminus \{\mathcal{S}\}$  onto  $\mathbb{R}^2$  and it endows the form

$$-\Delta u + \frac{4e^u}{1+e^u} = 4\pi \sum_{j=1}^k n_j \delta_{p_j} - 4\pi \sum_{j=1}^l m_j \delta_{q_j} \quad \text{in } \mathbb{R}^2. \quad (1.6)$$

It is pointed out in [31] that the points  $p_j$  with  $j = 1, \dots, k$  can be viewed as magnetic monopoles and the points  $q_j$  with  $j = 1, \dots, l$  as anti-monopoles; and they are also called magnetic vortices and anti-vortices respectively.

An important quantity for gauged sigma model is the total magnetic flux:

$$\mathcal{M}(\phi) = \int_{\mathbb{R}^2} F_{12}. \quad (1.7)$$

Here and in what follows, we denote

$$N = \sum_{j=1}^k n_j \quad \text{and} \quad M = \sum_{j=1}^l m_j.$$

When the gravitation constant  $G$  is replaced by zero, a layer's structure of solutions of (1.1) has been determined in the following result:

**Theorem 1.1** [10, 31] (i) If  $M = N - 1$ , then problem (1.6) has no solution.

(ii) If  $M < N - 1$ , then for any  $\beta \in [2, 2(N - M))$  problem (1.6) has a unique solution  $u_\beta$  verifying

$$\mathcal{M}(u_\beta) = 2\pi(2(N - M) + \beta)$$

with the following behaviour as  $|x| \rightarrow \infty$ ,

$$u_\beta(x) = \begin{cases} -\beta \ln |x| + O(1) & \text{if } \beta \in (2, 2(N - M)), \\ -2 \ln |x| - 2 \ln \ln |x| + O(1) & \text{if } \beta = 2. \end{cases}$$

Furthermore the correspondence  $\beta \mapsto u_\beta$  is decreasing.

(iii) If  $M < N - 1$  and  $u$  is a non-topological solution of (1.6) with finite total magnetic flux, i.e.  $\mathcal{M}(u) < \infty$ , then there exists a unique  $\beta \in [2, 2(N - M))$  such that  $u = u_\beta$ .

The study of these equations have been studied extensively, motivated by a large range of applications in physics such as the gauged sigma models with broken symmetry [32], the gravitational Maxwell gauged  $O(3)$  sigma model [7, 9, 26, 27], the self-dual Chern-Simons-Higgs model [8, 20], magnetic vortices [18], Toda system [19, 23], Liouville equation [17] and the references therein. It is also motivated by important questions in the theory of nonlinear partial differential equations [5, 28, 29], which has its own features in two dimensional space.

When  $a = 16\pi G$ , equation (1.1) governs the gravitational Maxwell gauged  $O(3)$  sigma model restricted to a plane. Because of the gravitational interaction between particles, the Lagrangian density becomes

$$\mathcal{L} = \frac{1}{4} g^{\mu\mu'} g^{\nu\nu'} F_{\mu\nu} F_{\mu'\nu'} + \frac{1}{2} D_\mu \phi \overline{D^\mu \phi} - \frac{1}{2} (1 - \vec{n} \cdot \phi)^2$$

with stress energy tensor

$$T_{\mu\nu} = g^{\mu'\nu'} F_{\mu\nu} F_{\mu'\nu'} + D_\mu \phi D_\nu \phi - g_{\mu\nu} \mathcal{L}.$$

We simplify the Einstein equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -8\pi G T_{\mu\nu},$$

where  $R_{\mu\nu}$  is the Ricci tensor and  $R$  is a scalar tensor of the metric in considering a metric conformal to the  $(2 + 1)$ -dimensional Minkowski one

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & e^\eta & 0 \\ 0 & 0 & e^\eta \end{pmatrix}.$$

Then

$$\frac{1}{2} e^{-\eta} \Delta \eta = -8\pi G T_{00},$$

where

$$T_{00} = \frac{1}{2} (e^{-\eta} F_{12} \pm (1 - \vec{n} \cdot \phi))^2 \pm e^{-\eta} F_{12} (1 - \vec{n} \cdot \phi) \pm e^{-\eta} \phi (D_1 \phi \times D_2 \phi) + \frac{1}{2} (D_1 \phi \pm \phi \times D_2 \phi)^2.$$

The minimum of the energy is achieved if and only if  $(\phi, A)$  satisfies the self-dual equations (the Bogomol'nyi equations)

$$D_1 \phi = \mp \phi \times D_2 \phi, \quad F_{12} = \pm e^\eta (1 - \vec{n} \cdot \phi).$$

Furthermore, a standard analysis yields equation (1.1). In particular, Yang in [33] studied equation (1.1) when there is only one concentrated pole, i.e.  $k = 1$  and  $l = 0$ . For multiple poles, Chae showed in [7] that problem (1.1) has a sequence of non-topological solutions  $u_\beta$  such that

$$u_\beta(x) = \beta \ln |x| + O(1) \quad \text{when } |x| \rightarrow \infty$$

for  $\beta \in (-\min\{6, 2(N - M)\}, -2)$ , when

$$aN < 1 \quad \text{and} \quad N - M \geq 2. \tag{1.8}$$

Under the assumption (1.8), the existence of solutions has been improved up to the range  $\beta \in (-2(N - M), -2)$  in [27]. However, these existence results do not show the role of the gravitation played in the gauged sigma model and the features of the interacting of the diffusion and the non-monotone nonlinearity of equation (1.1) in the whole two dimensional space.

## 1.2 Main results

Note that if we take into account the gravitation, the magnetic flux turns out to be

$$\mathcal{M}(u) = \int_{\mathbb{R}^2} \mathbf{P}(x) \frac{e^u}{(1 + e^u)^{1+a}} dx, \tag{1.9}$$

which, due to the potential and the decay to zero for  $\frac{e^t}{(1+e^t)^{1+a}}$  as  $t \rightarrow \infty$ , allows the existence of solutions with very wild behaviors at infinity. In fact, the following three types of solutions are considered in this paper

$$\left\{ \begin{array}{ll} \text{a solution } u \text{ of (1.1) is topological} & \text{if } \lim_{|x| \rightarrow +\infty} u(x) = \ell \in \mathbb{R}, \\ \text{a solution } u \text{ of (1.1) is non-topological of type I} & \text{if } \lim_{|x| \rightarrow +\infty} u(x) = -\infty, \\ \text{a solution } u \text{ of (1.1) is non-topological of type II} & \text{if } \lim_{|x| \rightarrow +\infty} u(x) = +\infty. \end{array} \right.$$

The first result of this paper deals with non-topological solutions of type I for (1.1). For such a task we introduce two important quantities:

$$\beta^\# = \max \left\{ -2(N-M), \frac{2-2aN}{a} \right\} \quad \text{and} \quad \beta^* = \min \{0, 2aN-2, \alpha^* - 2(N-M)\}, \quad (1.10)$$

where

$$\alpha^* := \frac{1}{2\pi} \int_{\mathbb{R}^2} \mathbf{P}(x) dx. \quad (1.11)$$

Notice that  $\alpha^* = \infty$  if  $an_j \geq 1$  for some  $j$  or  $aN \leq 1$ , otherwise  $\alpha^*$  is finite, in this case, a free parameter  $A_0$  should be taken into account. If  $aN \leq 1$ , we have that  $\beta^* = 2aN - 2 \leq 0$ .

**Theorem 1.2** *Let  $a = 16\pi G$ ,  $an_j < 1$  for  $j = 1, \dots, k$  and  $\mathcal{M}$  be the total magnetic flux given in (1.9).*

(i) *If*

$$aN \leq 1 \quad \text{and} \quad M < (1+a)N - 1, \quad (1.12)$$

*then for any  $\beta \in (-2(N-M), \beta^*)$ , problem (1.1) possesses a minimal solution  $u_{\beta, \min}$  satisfying*

$$u_{\beta, \min}(x) = \beta \ln |x| + O(1) \quad \text{as} \quad |x| \rightarrow +\infty.$$

*Moreover, for some real number  $c_*$ ,*

$$u_{\beta, \min}(x) = \beta \ln |x| + c_* + O(|x|^{-\frac{aN-\beta-2}{aN-\beta-1}}) \quad \text{as} \quad |x| \rightarrow +\infty \quad (1.13)$$

*and the total magnetic flux of the solution  $u_{\beta, \min}$  is  $2\pi[2(N-M) + \beta]$ , i.e.*

$$\mathcal{M}(u_{\beta, \min}) = 2\pi[2(N-M) + \beta]. \quad (1.14)$$

(ii) *If*

$$aN > 1 \quad \text{and} \quad M < N, \quad (1.15)$$

*then  $\beta^\# < 0$  and for any  $\beta \in (\beta^\#, 0)$ , problem (1.1) possesses a sequence of non-topological solutions  $u_{\beta, i}$  of type I satisfying*

$$u_{\beta, i}(x) = \beta \ln |x| + c_i + O(|x|^{-\frac{2aN-2\beta-2}{2aN-2\beta-1}}) \quad \text{as} \quad |x| \rightarrow \infty, \quad (1.16)$$

*where*

$$c_i < c_{i+1} \rightarrow \infty \quad \text{as} \quad i \rightarrow +\infty.$$

*Moreover, the total magnetic flux of the solutions  $\{u_{\beta, i}\}_i$  is  $2\pi[2(N-M) + \beta]$ .*

Note that our assumption (1.12) is much weaker than (1.8) and Theorem 1.2 provides a larger range of  $\beta$  for existence of solutions  $u_\beta$  verifying  $u_\beta = \beta \ln |x| + o(1)$  at infinity. In particular, the assumption that  $M < (1+a)N - 1$  implies that  $\beta^* > -2(N - M)$ , and our second interest is to consider this extremal case  $\beta = \beta^*$ , which is  $2aN - 2$  under the assumption (1.12).

**Theorem 1.3** *Assume that  $a = 16\pi G$ ,  $an_j < 1$  for  $j = 1, \dots, k$ , the magnetic flux  $\mathcal{M}$  is given by (1.9) and let (1.12) hold.*

*Then problem (1.1) possesses a minimal non-topological solution  $u_{\beta^*, \min}$  satisfying*

$$u_{\beta^*, \min}(x) = \beta^* \ln |x| - 2 \ln \ln |x| + O(1) \quad \text{as } |x| \rightarrow +\infty, \quad (1.17)$$

*and the total magnetic flux of  $u_{\beta^*, \min}$  is  $2\pi[2(N - M) + \beta^*]$ .*

The existence of non-topological solutions of type II to (1.1) states as follows.

**Theorem 1.4** *Assume that  $a = 16\pi G$ ,  $an_j < 1$  for  $j = 1, \dots, k$  and  $\beta^\#$  is given by (1.10), then for any  $\beta > \beta_+^\# = \max\{0, \beta^\#\}$ , problem (1.1) possesses a sequence of non-topological solutions  $\{u_{\beta, i}\}_i$  such that*

$$u_{\beta, i}(x) = \beta \ln |x| + c_i + O(|x|^{-\frac{2aN-2\beta-2}{2aN-2\beta-1}}) \quad \text{as } |x| \rightarrow +\infty, \quad (1.18)$$

where

$$c_i < c_{i+1} \rightarrow +\infty \quad \text{as } i \rightarrow +\infty.$$

Moreover, the total magnetic flux of the solutions  $\{u_{\beta, i}\}_i$  is  $2\pi[2(N - M) + \beta]$ .

Concerning topological solutions of (1.1), we have following result,

**Theorem 1.5** *Let  $a = 16\pi G$ ,  $an_j < 1$  for  $j = 1, \dots, k$  and (1.15) hold true.*

*Then problem (1.1) possesses infinitely many topological solutions  $u_{0, i}$  satisfying*

$$u_{0, i}(x) = c_i + O(|x|^{-\frac{2aN-2}{2aN-1}}) \quad \text{as } |x| \rightarrow \infty, \quad (1.19)$$

where

$$c_i < c_{i+1} \rightarrow \infty \quad \text{as } i \rightarrow \infty.$$

Moreover, the total magnetic flux of solutions  $\{u_{0, i}\}_i$  is  $4\pi(N - M)$ .

Note that Theorem 1.4 and Theorem 1.5 provide respectively infinitely many non-topological solutions of Type II and topological solutions. Furthermore, there is no upper bound for these solutions due to the failure of the Keller-Osserman condition for the nonlinearity  $\frac{4e^u}{(1+e^u)^{1+a}}$ , see [16, 22]. More precisely equation (1.1) admits no solution with boundary blow-up in a bounded domain. The existence of these solutions illustrates that the gravitation plays an important role in the Maxwell gauged  $O(3)$  sigma model:

- (i) the set of solutions is extended to topological and two types of non-topological solutions;
- (ii) the uniqueness fails for the solution under the given condition  $u_\beta(x) = \beta \ln |x| + O(1)$  at infinity;



Table 1: Non-topological solutions of Type I

Assumptions on $a, N, M$	range of $\beta$	solutions	asymptotic behavior at $\infty$
$aN \leq 1, M < (1+a)N - 1$	$(-2(N-M), \beta^*)$	Minimal	$\beta \ln  x  + O(1)$
$aN \leq 1, M < (1+a)N - 1$	$\beta^* = 2(aN - 1)$	Minimal	$\beta^* \ln  x  - 2 \ln \ln  x  + O(1)$
$N > M, aN > 1$	$(\beta^\#, 0)$	Multiple	$\beta \ln  x  + c_i + o(1), \lim_{i \rightarrow \infty} c_i = \infty$

Table 2: Non-topological solutions of Type II

range of $\beta$	solutions	asymptotic behavior at $\infty$
$(\beta_+^\#, \infty)$	Multiple	$\beta \ln  x  + c_i + o(1), \lim_{i \rightarrow \infty} c_i = \infty$

Table 3: Topological solutions

Assumptions on $a, N, M$	solutions	asymptotic behavior at $\infty$
$aN > 1, M < N$	Multiple	$c_i + o(1), \lim_{i \rightarrow \infty} c_i = \infty$

(iii) the numbers of magnetic poles  $N, M$  do no longer verify  $M < N + 1$ . In fact, for the non-topological solution of type I, it becomes  $M < (1+a)N + 1$ , but for the non-topological solution of type II, there is no restriction on  $N$  and  $M$ , if  $\beta > 0$  large enough.

Our existence statements of solutions of (1.1) are summarized in the three tables above.

The biggest difference with the case that  $a = 0$  is that the nonlinearity is no longer monotone, which makes more difficult to construct super and sub solutions to (1.1). Our main idea is to approximate the solution by monotone iterative schemes for some related equations with an increasing nonlinearity.

Finally, we concentrate on the nonexistence of solutions  $u_\beta$  for (1.1) with the behavior  $\beta \ln |x| + O(1)$  at infinity for some  $\beta$ .

**Theorem 1.6** *Assume that  $a = 16\pi G$  and  $an_j < 1$  for  $j = 1, \dots, k$ .*

(i) *If  $aN < 1$  and  $\beta^* < \beta < \frac{2-aN}{a}$ , then problem (1.1) has no solution  $u_\beta$  with the asymptotic behavior*

$$u_\beta(x) = \beta \ln |x| + o(\ln |x|) \quad \text{as } |x| \rightarrow \infty.$$

(ii) *If  $aN = 1$ , then problem (1.1) has no topological solution.*

The remaining of this paper is organized as follows. In Section 2, we present some decompositions of solutions of (1.1), some important estimates are provided and related forms of equations are considered. We prove that problem 1.1 has a minimal non-topological solution of Type I and minimal solutions in Section 3. Existence of infinitely many non-topological solutions of Type II is obtained in Section 4. Infinitely many topological solutions and minimal topological solution are constructed in Section 5. Finally, Section 6 deals with the classification of general non-topological solutions of (1.1) with infinite total magnetic flux.

## 2 Preliminary

### 2.1 Regularity

We start our analysis by considering the regularity of weak solutions of (1.1). Let  $\zeta$  be a smooth and increasing function over  $(0, \infty)$  such that

$$\zeta(t) = \begin{cases} \ln t & \text{for } 0 < t \leq 1/2, \\ 0 & \text{for } t \geq 1. \end{cases}$$

Set

$$\nu_1(x) = 2 \sum_{i=1}^k n_i \zeta\left(\frac{|x-p_i|}{\sigma}\right) \quad \text{and} \quad \nu_2(x) = 2 \sum_{j=1}^l m_j \zeta\left(\frac{|x-q_j|}{\sigma}\right), \quad (2.1)$$

where  $\sigma \in (0, 1)$  is chosen such that any two balls of

$$\{B_\sigma(p_i), B_\sigma(q_j) : i = 1, \dots, k, j = 1, \dots, l\}$$

do not intersect. We fix a positive number  $r_0 \geq e^e$  large enough such that  $B_\sigma(p_i), B_\sigma(q_j) \subset B_{r_0}(0)$  for  $i = 1, \dots, k$  and  $j = 1, \dots, l$ , and we denote

$$\Sigma_1 = \{p_1, \dots, p_k\}, \quad \Sigma_2 = \{q_1, \dots, q_l\} \quad \text{and} \quad \Sigma = \Sigma_1 \cup \Sigma_2.$$

If  $u$  is a weak solution of (1.1), we set

$$u = w - \nu_1 + \nu_2 \quad \text{in } \mathbb{R}^2 \setminus \Sigma, \quad (2.2)$$

then  $w$  is a weak solution of

$$-\Delta w + V \frac{e^w}{(e^{\nu_1 - \nu_2} + e^w)^{1+a}} = f_1 - f_2 \quad \text{in } \mathbb{R}^2, \quad (2.3)$$

with

$$V = \mathbf{P}e^{a(\nu_1 - \nu_2)}, \quad f_1 = 4\pi \sum_{i=1}^k n_i \delta_{p_i} - \Delta \nu_1 \quad \text{and} \quad f_2 = 4\pi \sum_{j=1}^l m_j \delta_{q_j} - \Delta \nu_2. \quad (2.4)$$

The functions  $f_1, f_2$  are smooth with compact support in  $B_{r_0}(0)$  and they satisfy

$$\int_{\mathbb{R}^2} (f_1 - f_2) dx = 4\pi(N - M). \quad (2.5)$$

**Proposition 2.1** *Assume that  $u$  is a weak solution of (1.1), then  $u$  is a classical solution of*

$$-\Delta u + \mathbf{P}(x) \frac{e^u}{(1 + e^u)^{1+a}} = 0 \quad \text{in } \mathbb{R}^2 \setminus \Sigma, \quad (2.6)$$

and  $w = u - \nu_1 + \nu_2$  is a classical solution of (2.3) in whole  $\mathbb{R}^2$ .

**Proof.** Let  $u$  be a weak solution of (1.1). Because  $\frac{e^u}{(1+e^u)^{1+a}}$  is uniformly bounded in  $\mathbb{R}^2$  and  $\mathbf{P}$  is locally bounded and smooth in  $\mathbb{R}^2 \setminus \Sigma$ , the function  $u$  is a classical solution of (2.6) in  $\mathbb{R}^2 \setminus \Sigma$ , and by standard regularity theory it belongs to  $C^\infty(\mathbb{R}^2 \setminus \Sigma)$ . Then  $w$  is a smooth locally bounded function in  $\mathbb{R}^2 \setminus \Sigma$  satisfying (2.3) an equation that we rewrite under the form

$$-\Delta w + h(\cdot, w) = f_1 - f_2 \quad \text{in } \mathcal{D}'(\mathbb{R}^2), \quad (2.7)$$

where the function  $h(x, z)$  is defined in  $\mathbb{R}^2 \times \mathbb{R}$  by

$$h(x, z) = \begin{cases} V(x) \frac{e^z}{(e^{\nu_1 - \nu_2} + e^z)^{1+a}} & \text{for } x \in \mathbb{R}^2 \setminus \Sigma, \\ 0 & \text{for } x \in \Sigma_2, \\ \sigma^{-2an_j} \prod_{i \neq k} |p_j - p_i|^{-2an_i} e^{-az} & \text{for } x = p_j \in \Sigma_1. \end{cases}$$

The function  $h$  is nonnegative and smooth in  $\mathbb{R}^2 \setminus \Sigma$  and continuous in  $\mathbb{R}^2 \times \mathbb{R}$ . Since  $w$  is smooth in  $\mathbb{R}^2 \setminus \Sigma$ , so is  $h(\cdot, w)$ . Next we set, with  $Z = e^z \geq 0$

$$\phi(Z) = \frac{Ze^{a(\nu_1 - \nu_2)}}{(e^{a(\nu_1 - \nu_2)} + Z)^{1+a}} \implies \phi'(Z) = \frac{e^{a(\nu_1 - \nu_2)} (e^{a(\nu_1 - \nu_2)} - aZ)}{(e^{a(\nu_1 - \nu_2)} + Z)^{2+a}}. \quad (2.8)$$

Then

$$\phi'(Z_0) = 0 \quad \text{if } Z_0 = \frac{e^{a(\nu_1 - \nu_2)}}{a} \implies \phi(Z_0) = \frac{a^a}{(a+1)^{1+a}} = \max\{\phi(Z) : Z > 0\}. \quad (2.9)$$

Hence

$$0 \leq h(x, w) \leq \mathbf{P}(x) \frac{a^a}{(a+1)^{1+a}}. \quad (2.10)$$

Because  $\mathbf{P}$  is locally bounded in  $\mathbb{R}^2 \setminus \Sigma_1$ , it follows by standard regularity arguments, (see e.g. [12]) that  $w$  belongs to  $W_{loc}^{2,r}(\mathbb{R}^2 \setminus \Sigma_1)$  for any  $r < \infty$ . Hence  $h(\cdot, w) \in C^{1,\theta}(\mathbb{R}^2 \setminus \Sigma_1)$  for any  $\theta \in (0, 1)$ , and finally  $w \in C^{3,\theta}(\mathbb{R}^2 \setminus \Sigma_1)$  is a strong solution in  $\mathbb{R}^2 \setminus \Sigma_1$ . In a neighborhood of  $\Sigma_1$  we write  $h$  under the form

$$h(x, z) = \mathbf{P}(x) e^{a\nu_1} \frac{e^{z - a\nu_2}}{(e^{\nu_1 - \nu_2} + e^z)^{1+a}}.$$

Since  $h$  is nonnegative,  $w$  satisfies

$$-\Delta w \leq f_1 - f_2 \quad \text{in } \mathcal{D}'(\mathbb{R}^2),$$

and as  $f_1 - f_2$  is bounded with compact support, it follows that  $w$  is locally bounded from above in  $\mathbb{R}^2$ . Furthermore there exist an open set  $\mathcal{O}$  such that  $\Sigma_1 \subset \mathcal{O}$  and  $\overline{\mathcal{O}} \cap \Sigma_2 = \emptyset$  and a function  $c_1 \in C(\overline{\mathcal{O}})$  such that

$$h(x, z) = c_1(x) \frac{e^z}{(e^{\nu_1 - \nu_2} + e^z)^{1+a}} \quad \text{for all } (x, z) \in \overline{\mathcal{O}} \times \mathbb{R}.$$

We fix  $p_j \in \Sigma_1$ , set  $r_j = \sup\{w(x) : x \in \overline{B}_\sigma(p_j)\}$  and  $v_j = r_j - w$ . Then  $v_j \geq 0$  in  $\overline{B}_\sigma(p_j)$  and

$$-\Delta v_j = f_2 - f_1 + c_1 \frac{e^{r_j - v_j}}{(e^{\nu_1 - \nu_2} + e^{r_j - v_j})^{1+a}} = f_2 - f_1 + c_1 e^{-ar_j} \frac{e^{-v_j}}{(e^{\nu_1 - \nu_2 - r_j} + e^{-v_j})^{1+a}}.$$

Since  $f_1, f_2$  are smooth, hence  $c_1 e^{-ar_j} \frac{e^{-v_j}}{(e^{\nu_1 - \nu_2 - r_j} + e^{-v_j})^{1+a}} \in L^1(B_\sigma(p_j))$  by [4]. If  $0 < \sigma' \leq \sigma$ , we denote by  $\phi_j^{B_{\sigma'}}$  the harmonic lifting of  $v_j|_{\partial B_{\sigma'}}$  in  $B_{\sigma'}(p_j)$  and put  $\tilde{v}_{\sigma'} = v_j - \phi_j^{B_{\sigma'}}$ . Then, for  $\sigma' \leq \sigma$ ,

$$\begin{cases} -\Delta \tilde{v}_{\sigma'} = f_2 - f_1 + c_1 e^{-ar_j} \frac{e^{-v_j}}{(e^{\nu_1 - \nu_2 - r_j} + e^{-v_j})^{1+a}} := F & \text{in } B_{\sigma'}(p_j), \\ \tilde{v}_{\sigma'} = 0 & \text{on } \partial B_{\sigma'}(p_j). \end{cases}$$

Let  $M^2(B_{\sigma'}(p_j))$  denote the Marcikiewicz space also known as the Lorentz space  $L^{2,\infty}(B_{\sigma'}(p_j))$ . Then there holds

$$\|\nabla \tilde{v}_{\sigma'}\|_{M^2(B_{\sigma'}(p_j))} \leq c_3 \|F\|_{L^1(B_{\sigma'}(p_j))}, \quad (2.11)$$

and the constant  $c_3$  is independent of  $\sigma'$ . We recall below John-Nirenberg's theorem [12, Theorem 7. 21]: *Let  $u \in W^{1,1}(G)$  where  $G \subset \Omega$  is convex and suppose there is a constant  $K$  such that*

$$\int_{G \cap B_r} |\nabla u| dx \leq Kr \quad \text{for any ball } B_r. \quad (2.12)$$

*Then there exist positive constants  $\mu_0$  and  $C$  such that*

$$\int_G \exp\left(\frac{\mu}{K} |u - u^G|\right) dx \leq C(\text{diam}(G))^2, \quad (2.13)$$

where  $\mu = \mu_0 |G|(\text{diam}(G))^{-2}$  and  $u^G$  is the average of  $u$  on  $G$ .

By (2.11) with  $G = B_{\sigma'}(p_j)$

$$\int_{B \cap B_r} |\nabla \tilde{v}_{\sigma'}| dx \leq c_4 r \|F\|_{L^1(B_{\sigma'}(p_j))} := K(\sigma') r, \quad (2.14)$$

and since  $|G|(\text{diam}(G))^{-2} = \pi$  we obtain

$$\int_{B_{\sigma'}(p_j)} \exp\left(\frac{\pi \mu_0}{K(\sigma')} |\tilde{v}_{\sigma'} - \tilde{v}_{\sigma'}^{B_{\sigma'}}|\right) dx \leq C \sigma'^2. \quad (2.15)$$

Hence, for any  $\kappa > 0$  there exists  $\sigma' \in (0, \sigma]$  such that

$$\int_{B_{\sigma'}(p_j)} \exp\left(\kappa |\tilde{v}_{\sigma'} - \tilde{v}_{\sigma'}^{B_{\sigma'}}|\right) dx \leq C \sigma'^2 \implies \int_{B_{\sigma'}(p_j)} \exp(\kappa \tilde{v}_{\sigma'}) dx \leq C \sigma'^2 \exp(\kappa \tilde{v}_{\sigma'}^{B_{\sigma'}}). \quad (2.16)$$

Now we observe that there holds in  $B_{\sigma'}(p_j)$ ,

$$|F| \leq |f_2 - f_1| + c_1 e^{-ar_j} e^{av_j} \leq |f_2 - f_1| + c_1 e^{a \sup |v_j|_{\partial B_{\sigma'}}} e^{a \tilde{v}_{\sigma'}}.$$

For  $\kappa > a$ ,

$$\int_{B_{\sigma'}(p_j)} |F(x)|^{\frac{\kappa}{a}} dx \leq 2^{\frac{\kappa}{a}-1} \int_{B_{\sigma'}(p_j)} \left( |f_2 - f_1|^{\frac{\kappa}{a}} + \left( c_1 e^{a \sup |v_j|_{\partial B_{\sigma'}}} \right)^{\frac{\kappa}{a}} e^{\kappa \tilde{v}_{\sigma'}} \right) dx.$$

By (2.16) the right-hand side of the above inequality is bounded, hence  $F \in L^{\frac{\kappa}{a}}(B_{\sigma'}(p_j))$ . Since  $\tilde{v}_{\sigma'}$  vanishes on  $\partial B_{\sigma'}(p_j)$ , it follows by  $L^p$  regularity theory that  $\tilde{v}_{\sigma'} \in W^{2, \frac{\kappa}{a}}(B_{\sigma'}(p_j)) \cap W_0^{1, \frac{\kappa}{a}}(B_{\sigma'}(p_j))$ . By Sobolev embedding theorem,  $\tilde{v}_{\sigma'} \in L^\infty(B_{\sigma'}(p_j))$ . Hence  $F \in L^\infty(B_{\sigma'}(p_j))$  and again  $\tilde{v}_{\sigma'} \in W^{2, q}(B_{\sigma'}(p_j))$  for any  $q \in [1, \infty)$  and thus  $\tilde{v}_{\sigma'} \in C^{1, \theta}(\overline{B_{\sigma'}(p_j)})$  for any  $\theta \in (0, 1)$ . Therefore  $v_j$  remains bounded in  $C^{1, \theta}(\overline{B_{\sigma''}(p_j)})$  for any  $\sigma'' < \sigma'$ . In a neighborhood of  $p_j$ ,  $x \mapsto |x - p_j|^{-2an_j} e^{2a\zeta(\frac{|x-p_j|}{\sigma})}$  is Hölder continuous (of order  $2an_j$  if  $2an_j < 1$ ), and so is  $x \mapsto \mathbf{P}(x) e^{a(\nu_1 - \nu_2)(x)}$ . For the same reason,  $x \mapsto \frac{e^{w(x)}}{(e^{(\nu_1 - \nu_2)(x)} + e^{w(x)})^{1+a}}$  is Hölder continuous (with the same exponent) near  $p_j$ . Finally we infer that there exists  $\theta \in (0, 1)$  such that  $v_j \in C^{2, \theta}(\overline{B_{\sigma''}(p_j)})$ , which implies that  $w \in C^{2, \theta}(\mathbb{R}^2)$  is a strong solution of (2.3) in  $\mathbb{R}^2$ .  $\square$

*Remark.* Since  $\nu_1$  and  $\nu_2$  have compact support, we note that a weak solution  $u_\beta$  with asymptotic behavior  $\beta \ln |x| + O(1)$  at infinity can be decomposed

$$u_\beta = w_\beta - \nu_1 + \nu_2, \quad (2.17)$$

where  $w_\beta$  is a classical solution of (2.3) with the same asymptotic behavior  $\beta \ln |x| + O(1)$  at infinity. In fact, we shall continue to take out the singular source at infinity of the solution  $w_\beta$  in our derivation of non-topological solutions of (1.1).

## 2.2 Basic estimates

The following estimates play an important role in our construction of solutions to (1.1).

**Lemma 2.1** *Let  $\Gamma$  be the fundamental solution of  $-\Delta$  in  $\mathbb{R}^2$ ,  $F \in L_{loc}^p(\mathbb{R}^2)$ ,  $p > 1$ , with support in  $\overline{B_R(0)}$  for some  $R > 0$  such that*

$$\int_{\mathbb{R}^2} F(x) dx = 0. \quad (2.18)$$

*Then there holds*

$$|\Gamma * F(x)| \leq \frac{R}{|x|} \|F\|_{L^1(\mathbb{R}^2)} \quad \text{for } |x| > 4R, \quad (2.19)$$

*and, for some  $c_1 > 0$  depending on  $p$  and  $R$ ,*

$$\|\Gamma * F\|_{L^\infty(\mathbb{R}^2)} \leq c_1 \|F\|_{L^p(\mathbb{R}^2)}. \quad (2.20)$$

**Proof.** As  $\text{supp}(F) \subset \overline{B_R(0)}$ ,  $F \in L^1(\mathbb{R}^2)$  by Hölder. Since (2.18) holds, we have for  $|x| > 4R$ ,

$$\begin{aligned} |\Gamma * F(x)| &= \frac{1}{2\pi} \left| \int_{B_R(0)} \ln|x-y| F(y) dy - \int_{B_R(0)} \ln|x| F(y) dy \right| \\ &= \frac{|x|^2}{2\pi} \left| \int_{B_{\frac{R}{|x|}}(0)} \ln|e_x - z| F(|x|z) dz \right| \\ &\leq \frac{|x|^2}{\pi} \int_{B_{\frac{R}{|x|}}(0)} |z| |F(|x|z)| dz \\ &\leq \frac{R}{|x|} \|F\|_{L^1(\mathbb{R}^2)}, \end{aligned}$$

where  $e_x = \frac{x}{|x|}$ , we have used (2.18) and the fact that

$$|\ln|e_x - z|| \leq 2|z| \leq 2\frac{R}{|x|} \quad \text{for any } z \in B_{R/|x|}(0) \subset B_{1/4}(0).$$

Therefore, (2.19) is proved. On the other hand, for  $|x| \leq 4R$ , we have that

$$\begin{aligned} |\Gamma * F(x)| &= \frac{1}{2\pi} \left| \int_{B_R(0)} F(y) \ln|x-y| dy \right| \\ &\leq \left( \int_{B_R(0)} |F(y)|^p dx \right)^{\frac{1}{p}} \left( \int_{B_R(0)} |\ln|x-y||^{p'} dx \right)^{\frac{1}{p'}} \\ &\leq c_p \|F\|_{L^p(\mathbb{R}^2)}, \end{aligned}$$

where  $p' = \frac{p}{p-1}$  and  $c_p = \max_{|x| \leq 4R} (\int_{B_R(0)} |\ln|x-y||^{p'} dx)^{\frac{1}{p'}}$ . Thus, (2.20) follows and the proof is complete.  $\square$

For functions with non-compact supports, we have the following estimates.

**Lemma 2.2** *Let  $F \in L^p_{loc}(\mathbb{R}^2)$  satisfy that*

$$\int_{\mathbb{R}^2} F(x) dx = 0 \tag{2.21}$$

and

$$|F(x)| \leq c_2 |x|^{-\tau} \quad \text{for } |x| \geq r, \tag{2.22}$$

for some  $\tau > 2$ ,  $c_2 > 0$  and  $r > 0$ . Then

$$\|\Gamma * F\|_{L^\infty(\mathbb{R}^2)} \leq c_3$$

and

$$|x| |\nabla \Gamma * F(x)| + |\Gamma * F(x)| \leq \frac{c_4}{(\tau-2)^2} |x|^{-\frac{\tau-2}{\tau-1}} \quad \text{for } |x| \geq r_0 \text{ large enough,} \tag{2.23}$$

where  $c_3, c_4 > 0$ .

**Proof.** If  $F \in L^p_{loc}(\mathbb{R}^2)$  satisfies (2.22), then  $F \in L^1(\mathbb{R}^2)$ . Let  $\eta_r : \mathbb{R}^2 \rightarrow [0, 1]$  be a smooth and radially symmetric function such that

$$\eta_r = 1 \text{ in } B_r(0), \quad \eta_r = 0 \text{ in } B_{r+1}(0)$$

and denote

$$F_1 = F\eta_r - \left( \int_{\mathbb{R}^2} F\eta_r dx \right) \frac{\eta_r}{\|\eta_r\|_{L^1(\mathbb{R}^2)}}, \quad F_2 = F - F_1.$$

By (2.21), we have that

$$\int_{\mathbb{R}^2} F_1 dx = \int_{\mathbb{R}^2} F_2 dx = 0.$$

Since  $F_1 \in L^p_{loc}(\mathbb{R}^2)$ , with compact support, then by Lemma 2.1,  $\Gamma * F_1$  is bounded and satisfies (2.19). Concerning  $F_2$ , we have

$$F_2 = F - F_1 = \frac{\int_{\mathbb{R}^2} F\eta_r dx}{\|\eta_r\|_{L^1(\mathbb{R}^2)}} \quad \text{on } B_r$$

and it satisfies (2.22) on  $B_r^c$ , with may be another constant. It is locally bounded hence  $\Gamma * F_2$  is also locally bounded in  $\mathbb{R}^2$ . If (2.22) holds true we next show that  $F_2$  verifies (2.23).

Since  $\int_{\mathbb{R}^2} F_2 dx = 0$ , then for all  $|x| > 4r$  and  $R \in (r, \frac{|x|}{4})$  which will be chosen latter on

$$\begin{aligned} 2\pi(\Gamma * F_2)(x) &= |x|^2 \int_{\mathbb{R}^2} \ln |e_x - z| F_2(|x|z) dz + |x|^2 \ln |x| \int_{\mathbb{R}^2} F_2(|x|z) dz \\ &= |x|^2 \int_{B_{R/|x|}(0)} \ln |e_x - z| F_2(|x|z) dz + |x|^2 \int_{B_{1/2}(e_x)} \ln |e_x - z| F_2(|x|z) dz \\ &\quad + |x|^2 \int_{\mathbb{R}^2 \setminus (B_{R/|x|}(0) \cup B_{1/2}(e_x))} \ln |e_x - z| F_2(|x|z) dz \\ &=: I_1(x) + I_2(x) + I_3(x), \end{aligned}$$

using the fact that  $B_{R/|x|}(0) \cap B_{1/2}(e_x) = \emptyset$ . By direct computation, we have that

$$\begin{aligned} |I_1(x)| &\leq |x|^2 \int_{B_{R/|x|}(0)} |z| |F_2(|x|z)| dz \\ &= 2 \frac{R}{|x|} \int_{B_R(0)} |F_2(y)| dy \\ &\leq 2 \frac{R}{|x|} \|F_2\|_{L^1(\mathbb{R}^2)}. \end{aligned}$$

For  $z \in B_{1/2}(e_x)$ , there holds  $|x||z| \geq \frac{1}{2}|x| > 2r$ , then  $|F(|x|z)| \leq c_2|x|^{-\tau}|z|^{-\tau}$  and

$$\begin{aligned} |I_2(x)| &\leq c_2|x|^{2-\tau} \int_{B_{1/2}(e_x)} (-\ln |e_x - z|) |z|^{-\tau} dz \\ &\leq 2^\tau c_2|x|^{2-\tau} \int_{B_{1/2}(e_x)} (-\ln |e_x - z|) dz \\ &\leq c_4 R^{2-\tau}, \end{aligned}$$

where  $c_4 = 2^{2(N-M)} c_2 \left( \int_{B_{1/2}(0)} (-\ln|z|) dz \right)$  can be chosen independently of  $\tau$  in  $(2, 2(N-M))$ . Next, if  $z \in \mathbb{R}^2 \setminus (B_{R/|x|}(0) \cup B_{1/2}(e_x))$ , then  $|\ln|e_x - z|| \leq \ln(1+|z|)$  and  $|F(|x|z)| \leq c_4|x|^{-\tau}|z|^{-\tau}$ , since  $|z| \geq \frac{R}{|x|} > \frac{r}{|x|}$ . By integration by parts we get

$$\begin{aligned} |I_3(x)| &\leq c_5|x|^{2-\tau} \int_{\mathbb{R}^2 \setminus B_{R/|x|}(0)} \ln(1+|z|) |z|^{-\tau} dz \\ &\leq \frac{2\pi c_5}{\tau-2} R^{2-\tau} \ln\left(1 + \frac{R}{|x|}\right) + \frac{2\pi c_5}{(\tau-2)^2} R^{2-\tau} \\ &\leq \frac{2\pi c_5}{(\tau-2)^2} ((\tau-2)\ln 2 + 1) R^{2-\tau}. \end{aligned}$$

Thus, taking  $R = |x|^{\frac{1}{\tau-1}}$  and  $|x|$  sufficiently large (certainly  $R \in (r, \frac{|x|}{4})$  is satisfied), we have

$$\begin{aligned} |\Gamma * F_2(x)| &\leq \frac{R}{\pi|x|} \|F\|_{L^1(\mathbb{R}^2)} + \frac{c_5}{2\pi} R^{2-\tau} + \frac{c_5}{(\tau-2)^2} \left( 2(N-M-1)\ln(e+1) + 1 \right) R^{2-\tau} \\ &\leq \frac{c_6}{(\tau-2)^2} |x|^{-\frac{\tau-2}{\tau-1}}, \end{aligned}$$

where  $c_6 > 0$  can be chosen independently of  $\tau$ . In order to prove the gradient estimate, we denote by  $(r, \theta)$  the polar coordinates in  $\mathbb{R}^2$ , set  $t = \ln r$  and

$$\omega(t, \theta) = \tilde{\omega}(r, \theta) = r^{-\frac{\tau-2}{\tau-1}} \Gamma * F(r, \theta) \quad \text{and} \quad \phi(t, \theta) = r^\tau F(r, \theta).$$

Then  $\omega$  and  $\phi$  are bounded on  $[\ln r_1, \infty) \times S^1$  where there holds

$$\mathcal{L}\omega := \frac{\partial^2 \omega}{\partial t^2} - 2\frac{\tau-2}{\tau-1} \frac{\partial \omega}{\partial t} + \left( \frac{\tau-2}{\tau-1} \right)^2 \omega + \frac{\partial^2 \omega}{\partial \theta^2} = \tau^{-\frac{(\tau-2)^2}{\tau-1}} \phi.$$

Since the operator  $\mathcal{L}$  is uniformly elliptic on  $[\ln r_1, \infty) \times S^1$ , for any  $T > \ln r_1 + 2$  by standard estimates there holds

$$\sup_{[T-1, T+1] \times S^1} \left( \left| \frac{\partial \omega}{\partial \theta} \right| + \left| \frac{\partial \omega}{\partial t} \right| \right) \leq c_{\mathcal{L}} \sup_{[T-2, T+2] \times S^1} \left( |\omega| + \left| \tau^{-\frac{(\tau-2)^2}{\tau-1}} \phi \right| \right) \leq c_4^*$$

and  $c_4^*$  does not depend on  $T$ . As  $|x| |\nabla \tilde{\omega}(x)| = \left( \left| \frac{\partial \omega}{\partial \theta} \right|^2 + \left| \frac{\partial \omega}{\partial t} \right|^2 \right)^{\frac{1}{2}}$ , this implies the claim.  $\square$

The decay estimate on the gradient does not use the fact that identity (2.21) holds. It is actually more general.

**Corollary 2.1** *Let  $F \in L_{loc}^p(\mathbb{R}^2)$  satisfy (2.22) with  $\tau > 2$  and  $w$  be a solution of*

$$-\Delta w = F \quad \text{in } \mathbb{R}^2. \quad (2.24)$$

(i) *If  $\lim_{|x| \rightarrow \infty} |x|^{\frac{\tau-2}{\tau-1}} |w(x)| < \infty$ , then*

$$|\nabla w(x)| \leq c'_4 |x|^{-\frac{2\tau-3}{\tau-1}} \quad \text{for } |x| \geq r_0. \quad (2.25)$$

(ii) *If there exists a constant  $c$  such that  $w(x) = c + O(|x|^{-\frac{\tau-2}{\tau-1}})$  when  $|x| \rightarrow \infty$ , then estimate (2.25) holds.*



**Proof.** The assertion (i) is clear since the starting point of the gradient estimate in the previous lemma is

$$|w(x)| \leq C|x|^{-\frac{\tau-2}{\tau-1}} \quad \text{for } |x| \text{ large enough.}$$

For assertion (ii), we set  $w(x) = c + \tilde{w}(x)$  where  $|\tilde{w}(x)| = O(|x|^{-\frac{\tau-2}{\tau-1}})$ . Then  $-\Delta \tilde{w} = -\Delta w$  and  $\nabla w = \nabla \tilde{w}$ . We conclude by (i).  $\square$

When  $\tau = 2$  Lemma 2.2 is no longer valid, however the following limit case is available.

**Lemma 2.3** *Let  $F \in L^p_{loc}(\mathbb{R}^2)$  satisfy (2.21) and*

$$|F(x)| \leq c'_2 |x|^{-2} (\ln |x|)^{-\nu} \quad \text{for } |x| \geq r, \quad (2.26)$$

*for some  $\nu > 2$ ,  $c'_2 > 0$  and  $r > 0$ . Then*

$$\|\Gamma * F\|_{L^\infty(\mathbb{R}^2)} \leq c'_3$$

*and*

$$|x| |\nabla \Gamma * F(x)| + |\Gamma * F(x)| \leq c'_4 (\ln |x|)^{-\nu} \quad \text{for } |x| \geq r_0 \text{ large enough,} \quad (2.27)$$

*where  $c'_3, c'_4 > 0$  and  $r_0 > r$ .*

**Proof.** The assumption (2.26) jointly with  $F \in L^p_{loc}(\mathbb{R}^2)$  implies  $F \in L^1(\mathbb{R}^2)$ . We write  $F = F_1 + F_2$  in the same way as in Lemma 2.2. Clearly  $\Gamma * F_1$  is uniformly bounded and satisfies (2.19) and (2.20). Then for  $|x| > 4r > 4$  and  $R \in (r, \frac{|x|}{4}]$ ,

$$2\pi(\Gamma * F_2)(x) = I_1(x) + I_2(x) + I_3(x),$$

where  $I_1, I_2$  and  $I_3$  are defined in the proof of Lemma 2.2 and where  $|I_1(x)| \leq 2\frac{R}{|x|} \|F_2\|_{L^1(\mathbb{R}^2)}$ .

When  $z \in B_{\frac{1}{2}}(e_x)$  we have  $|x||z| \geq \frac{1}{2}|x| > 2r$ , hence

$$|F_2(|x|z)| \leq c'_2 |x|^{-2} |z|^{-2} (\ln |x| + \ln |z|)^{-\nu} \leq c'_2 |x|^{-2} |z|^{-2} |\ln |x| - \ln 2|^{-\nu} \quad (2.28)$$

and

$$I_2(x) \leq -c'_2 |\ln |x| - \ln 2|^{-\nu} \int_{B_{\frac{1}{2}}(e_x)} \ln |z - e_x| |z|^{-2} dz \leq c''_4 (\ln |x|)^{-\nu}.$$

Finally, if  $z \in \mathbb{R}^2 \setminus (B_{R/|x|}(0) \cup B_{1/2}(e_x))$ , then  $|\ln |e_x - z|| \leq \ln(1 + |z|)$  and

$$|F_2(|x|z)| \leq c''_4 (1 + |x||z|)^{-2} (\ln(1 + |x||z|))^{-\nu} \leq c''_4 |x|^{-2} |z|^{-2} (\ln(1 + |x||z|))^{-\nu}.$$

Since  $|z| \geq \frac{R}{|x|} > \frac{r}{|x|}$ , we have

$$I_3(x) \leq c'_5 \int_{\frac{R}{|x|}}^{\infty} \ln(1+t) (\ln(1+t|x|))^{-\nu} \frac{dt}{t} \leq c'_5 \int_R^{\infty} (\ln(1+s))^{1-\nu} \frac{ds}{s}.$$

Since  $R > r > 1$ ,

$$I_3(x) \leq c'_6 \int_R^{\infty} (\ln(1+s))^{1-\nu} \frac{ds}{1+s} = \frac{c'_6}{\nu(\ln(1+R))^\nu}.$$

If we choose  $R = \frac{|x|}{4}$ , we derive that  $(\ln(1 + |x|))^\nu (\Gamma * F)(x)$  remains uniformly bounded on  $\mathbb{R}^2$ .

Next we prove the gradient estimate. Setting  $t = \ln r$ ,  $\omega(t, \theta) = (\Gamma * F)t, \theta$  and  $\phi(t, \theta) = F(r, \theta)$ , then

$$\mathcal{L}\omega := \frac{\partial^2 \omega}{\partial t^2} + \frac{\partial^2 \omega}{\partial \theta^2} = \phi$$

and  $|\omega(t, \theta)| \leq c'_7 t^{-\nu}$  and  $|\phi(t, \theta)| \leq c'_7 t^{-\nu}$  for  $t \geq t_1$ . Since the operator  $\mathcal{L} = \frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial \theta^2}$  is uniformly elliptic we have for,  $T \geq \max\{4, t_1\}$ ,

$$\sup_{[T-1, T+1] \times S^1} \left( \left| \frac{\partial \omega}{\partial \theta} \right| + \left| \frac{\partial \omega}{\partial t} \right| \right) \leq c_{\mathcal{L}} \sup_{[T-2, T+2] \times S^1} (|\omega| + |\phi|) \leq 2c_{\mathcal{L}} c'_7 (T-2)^{-\nu} \leq \tilde{c}_7^* T^{-\nu}.$$

Returning to the variable  $x$ , we infer (2.27).  $\square$

Similarly as in Corollary 2.1, the following extension of (2.27) holds.

**Corollary 2.2** *Let  $F \in L^p_{loc}(\mathbb{R}^2)$  satisfy (2.26) with  $\nu > 2$  and  $w$  satisfiesf (2.24).*

(i) *If  $\lim_{|x| \rightarrow \infty} (\ln |x|)^\nu |w(x)| < \infty$ , then*

$$|\nabla w(x)| \leq \tilde{c}_4 |x|^{-1} (\ln |x|)^{-\nu} \quad \text{for } |x| \geq r_0. \quad (2.29)$$

(ii) *If there exists a constant  $c$  such that  $w(x) = c + O((\ln |x|)^{-\nu})$  when  $|x| \rightarrow +\infty$ , then estimate (2.29) holds.*

### 2.3 Related problems with increasing nonlinearity

In order to remove the condition  $\beta \ln |x| + O(1)$  as  $|x| \rightarrow \infty$  satisfied by the solutions of (1.1), we introduce two functions  $\lambda$  and  $\Lambda$ , which are positive smooth functions such that

$$\lambda(x) = |x|, \quad \Lambda(x) = \ln |x| \quad \text{for } |x| \geq e^e. \quad (2.30)$$

Since  $\Delta \Lambda = 0$  in  $B_{e^e}^c(0)$ ,

$$\Delta \ln \Lambda = \frac{\Delta \Lambda}{\Lambda} - \frac{|\nabla \Lambda|^2}{\Lambda^2} = -\frac{1}{|x|^2 (\ln |x|)^2} \quad \text{in } B_{e^e}^c(0) \quad (2.31)$$

and

$$\frac{1}{2\pi} \int_{\mathbb{R}^2} (\Delta \ln \lambda) dx = 1, \quad (2.32)$$

$$\begin{aligned} \frac{1}{2\pi} \int_{\mathbb{R}^2} (\Delta \ln \Lambda) dx &= \lim_{r \rightarrow +\infty} \frac{1}{2\pi} \int_{\partial B_r(0)} \frac{\nabla \Lambda(x)}{\Lambda(x)} \cdot \frac{x}{|x|} d\omega(x) \\ &= \lim_{r \rightarrow +\infty} \frac{1}{r \ln r} = 0. \end{aligned}$$

In what follows we classify the solutions of the following equations

$$-\Delta u + W F_i(\lambda^\beta e^u) = g_\beta \quad \text{in } \mathbb{R}^2, \quad (2.33)$$

where  $i = 1, 2$ ,  $F_1(s) = s$ ,  $F_2(\cdot, s) = \frac{s}{e^{(\nu_1 - \nu_2)(\cdot) + s}}$ ,

$$g_\beta = f_1 - f_2 + \beta \Delta \ln \lambda, \quad (2.34)$$

and where  $W$  satisfies the following assumption:

$(\mathcal{W}_0)$  The function  $W$  is positive and locally Hölder continuous in  $\mathbb{R}^2 \setminus \Sigma_1$  and

$$W(x) \leq c_7 |x - p_j|^{-\tau_{p_j}} \quad \text{in } B_\sigma(p_j) \quad \text{and} \quad \limsup_{|x| \rightarrow +\infty} W(x) |x|^{\gamma_\infty} < +\infty,$$

where  $c_7 > 0$ ,  $\tau_{p_j} \in [0, 2)$  and  $\gamma_\infty > 0$ .

It is important to note that from (2.5), (2.32) and (2.34), there holds

$$\int_{\mathbb{R}^2} g_\beta dx = 2\pi[2(N - M) + \beta]. \quad (2.35)$$

**Theorem 2.1** Assume that  $F_1(s) = s$ ,  $F_2(x, s) = \frac{s}{e^{(\nu_1 - \nu_2)(x) + s}}$  and  $g_\beta$  is a Hölder continuous function with compact support in  $B_{r_0}(0)$  satisfying the relation (2.35) for some nonnegative integers  $N$  and  $M$ . Let  $W$  verify  $(\mathcal{W}_0)$  with

$$\gamma_\infty > \beta + 2. \quad (2.36)$$

(i) Then problem (2.33) with  $i = 1$  has a unique bounded solution  $v$  verifying, for some  $c_\beta \in \mathbb{R}$ ,

$$v(x) = c_\beta + O(|x|^{-\frac{\gamma_\infty - \beta - 2}{\gamma_\infty - \beta - 1}}) \quad \text{and} \quad |\nabla v(x)| = O(|x|^{-1 - \frac{\gamma_\infty - \beta - 2}{\gamma_\infty - \beta - 1}}) \quad \text{as } |x| \rightarrow +\infty. \quad (2.37)$$

(ii) Assume additionally that  $2(N - M) + \beta > 0$  and

$$2\pi[2(N - M) + \beta] < \int_{\mathbb{R}^2} W dx \leq +\infty. \quad (2.38)$$

Then problem (2.33) with  $i = 2$  has a unique bounded solution verifying

$$v(x) = c_\beta + O(|x|^{-\frac{\gamma_\infty + \beta - 2}{\gamma_\infty + \beta - 1}}) \quad \text{and} \quad |\nabla v(x)| = O(|x|^{-1 - \frac{\gamma_\infty + \beta - 2}{\gamma_\infty + \beta - 1}}) \quad \text{as } |x| \rightarrow +\infty. \quad (2.39)$$

**Proof.** Step 1. Since  $0 \leq \tau_{p_j} < 2$ ,  $W \in L^1_{loc}(\mathbb{R}^N)$ . For  $t \in \mathbb{R}$ , we set

$$h_{i,t}(x) = W(x) F_i(x, \lambda^\beta(x) e^t) \quad \forall x \in \mathbb{R}^2 \setminus \Sigma_1.$$

Notice that  $h_{2,t}$  is defined on  $\Sigma_2$  by

$$h_{2,t}(q_j) = 0 = \lim_{x \rightarrow q_j} h_{2,t}(x) \quad \text{for all } q_j \in \Sigma_2.$$

The function  $h_{i,t}$  is Hölder continuous in  $\mathbb{R}^2 \setminus \Sigma_1$ ,  $t \mapsto h_{i,t}$  is increasing in  $\mathbb{R}^2 \setminus \Sigma_1$ , and there holds

$$\begin{aligned} h_{1,t} &\rightarrow \infty \quad \text{locally in } \mathbb{R}^2 \setminus \Sigma_1 \quad \text{as } t \rightarrow +\infty, \\ h_{2,t} &\rightarrow W \quad \text{locally in } \mathbb{R}^2 \setminus \Sigma_1 \quad \text{as } t \rightarrow +\infty. \end{aligned}$$

Furthermore,

$$h_{i,t} \rightarrow 0 \quad \text{locally in } \mathbb{R}^2 \setminus \Sigma_1 \quad \text{as } t \rightarrow -\infty, \quad i = 1, 2.$$

By  $(\mathcal{W}_0)$ , it yields that

$$h_{1,t}(x) \leq c_8 e^t |x|^{-\gamma_\infty + \beta} \quad \text{for } |x| \geq r_1 \quad (2.40)$$

for some  $r_1 > 0$ . Since  $-\gamma_\infty + \beta < -2$ , we have that

$$\lim_{t \rightarrow -\infty} \int_{\mathbb{R}^2} h_{1,t}(x) dx = 0.$$

Concerning  $h_2$ , we have  $(\nu_1 - \nu_2)(x)(x) = 0$  if  $\text{dist}(x, \Sigma) \geq \sigma$ , and there holds

$$F_2(x, \lambda^\beta(x) e^t) = \frac{\lambda^\beta(x) e^t}{1 + \lambda^\beta(x) e^t} = \frac{|x|^\beta e^t}{1 + |x|^\beta e^t} \quad \text{for } |x| \geq r_1.$$

Then

$$h_{2,t}(x) \leq c_9 e^t |x|^{-\gamma_\infty - \beta_-} \quad \text{for } |x| \geq r_1, \quad (2.41)$$

which implies

$$\lim_{t \rightarrow -\infty} \int_{\mathbb{R}^2} h_{2,t}(x) dx = 0.$$

We claim that there exists  $t_i \in \mathbb{R}$  such that

$$\int_{\mathbb{R}^2} h_{i,t_i}(x) dx = \int_{\mathbb{R}^2} g_\beta(x) dx = 2\pi[2(N - M) + \beta]. \quad (2.42)$$

From the definition of  $F_i$ , (2.38) and the assumption on  $g_\beta$ ,

$$\lim_{t \rightarrow +\infty} \int_{\mathbb{R}^2} h_{1,t}(x) dx = \infty \quad \text{and} \quad \lim_{t \rightarrow +\infty} \int_{\mathbb{R}^2} h_{2,t}(x) dx = \int_{\mathbb{R}^2} W dx > \int_{\mathbb{R}^2} g_\beta dx.$$

Since  $t \mapsto \int_{\mathbb{R}^2} h_{i,t}(x) dx$  is continuous and increasing, it follows by the mean value theorem that there exists  $t_i \in \mathbb{R}$  such that

$$\int_{\mathbb{R}^2} h_{i,t_i}(x) dx = \int_{\mathbb{R}^2} g_\beta(x) dx.$$

*Step 2.* We use Lemma 2.2 to obtain some basic estimates on  $w_{0,i} = \Gamma * (g_\beta - h_{i,t_i})$ , taking into account the fact that  $\int_{\mathbb{R}^2} (g_\beta - h_{i,t_i}) dx = 0$  and

$$-\Delta w_{0,i} = g_\beta - h_{i,t_i} \quad \text{in } \mathbb{R}^2.$$

The function  $g_\beta$  is smooth with compact support, functions  $h_{i,t_i}$  are locally integrable in  $\mathbb{R}^2$  and satisfy

$$|h_{1,t_1}(x)| \leq c_{10} |x|^{-\gamma_\infty - \beta} \quad \text{and} \quad |h_{2,t_2}(x)| \leq c_{10} |x|^{-\gamma_\infty - \beta_-} \quad \text{for } |x| \text{ large enough.}$$

Since (2.43) holds, then, by Lemma 2.2, the function  $w_{0,i}$  is uniformly bounded in  $\mathbb{R}^2$ ,

$$|w_{0,i}(x)| \leq c_{11} |x|^{q_i} \quad \text{and} \quad |\nabla w_{0,i}(x)| \leq c_{12} |x|^{q_i - 1} \quad \text{for } |x| \text{ large enough,} \quad (2.43)$$

where

$$\varrho_1 = -\frac{\gamma_\infty + \beta - 2}{\gamma_\infty + \beta - 1} \quad \text{and} \quad \varrho_2 = -\frac{\gamma_\infty + \beta_- - 2}{\gamma_\infty + \beta_- - 1}. \quad (2.44)$$

*Step 3.* In order to apply the classical iterative method we need to construct suitable supersolutions and subsolutions for equation (2.33).

*Construction of the supersolution.* Set  $\bar{v}_i = (t_i)_+ + w_{0,i} + \|w_{0,i}\|_{L^\infty(\mathbb{R}^2)}$ , then

$$\begin{aligned} -\Delta \bar{v}_i + W F_i(\lambda^\beta e^{\bar{v}_i}) &= g_\beta - W F_i(\lambda^\beta e^{t_i}) + W F_i(\lambda^\beta e^{\bar{v}_i}) \\ &\geq g_\beta, \end{aligned}$$

since  $F_i(\lambda^\beta e^{\bar{v}_i}) \geq F_i(\lambda^\beta e^{t_i})$  as  $\bar{v}_i \geq t_i$ . Hence  $\bar{v}_i$  is a super solution of (2.33) for  $i = 1, 2$ .

*Construction of the subsolution.* Set  $\underline{v}_i = -(t_i)_- + w_{0,i} - \|w_{0,i}\|_{L^\infty(\mathbb{R}^2)}$ , then

$$-\Delta \underline{v}_i + W F_i(\lambda^\beta e^{\underline{v}_i}) = g_\beta - W F_i(\lambda^\beta e^{t_i}) + W F_i(\lambda^\beta e^{\underline{v}_i}) \leq g_\beta,$$

since  $F_i(\lambda^\beta e^{\underline{v}_i}) \leq F_i(\lambda^\beta e^{t_i})$  as  $\underline{v}_i \leq t_i$ . Hence  $\underline{v}_i$  is a subsolution of (2.33) for  $i = 1, 2$ . As  $\bar{v}_i > \underline{v}_i$  in  $\mathbb{R}^2$  by a standard iterating process, see [30, Section 2.4.4], there exists a solution  $v_i$  of (2.33) such that

$$\underline{v}_i \leq v_i \leq \bar{v}_i \quad \text{in } \mathbb{R}^2.$$

Note that  $v_i$  belongs to  $C^2(\mathbb{R}^2 \setminus \Sigma_1) \cap C(\mathbb{R}^2) \cap L^\infty(\mathbb{R}^2)$ .

*Uniqueness:* Let  $\tilde{v}_i$  be another solution of (2.33) and  $w_i = \tilde{v}_i - v_i$ , then

$$\begin{aligned} \Delta(w_i^2) &= 2w_i \Delta w_i + 2|\nabla w_i|^2 \geq 2w_i \Delta w_i \\ &= 2w_i \left( F_i(\lambda^\beta e^{\tilde{v}_i}) - F_i(\lambda^\beta e^{v_i}) \right) \geq 0, \end{aligned}$$

hence  $w_i^2$  is bounded and subharmonic in  $\mathbb{R}^2$ . Thus  $w_i^2$  is a constant by Liouville's theorem, that is  $\tilde{v}_i = v_i + c$ . Then  $F_i(\lambda^\beta e^{v_i}) = F_i(\lambda^\beta e^{v_i+c})$ . Thus  $c = 0$  and uniqueness follows. We denote by  $v_{\beta,i}$  this unique solution.

*Step 3: asymptotic expansion.* Now we shall employ Lemma 2.2 with  $\Phi_i = W F_i(\lambda^\beta e^t) - g_\beta$ , where  $g_\beta$  has compact support and (2.43) holds, thus

$$\limsup_{|x| \rightarrow \infty} \left( |\Phi_1(x)| |x|^{\gamma_\infty + \beta} + |\Phi_2(x)| |x|^{\gamma_\infty + \beta_-} \right) < +\infty.$$

Therefore we have that

$$\limsup_{|x| \rightarrow \infty} |\Gamma * \Phi_i(x)| |x|^{-\varrho_i} < +\infty. \quad (2.45)$$

The function  $w = v_{\beta,i} - \Gamma * \Phi_i$  is harmonic and bounded, hence it is constant by Louville theorem. Denote this constant by  $c_{\beta,i}$ , we deduce that

$$v_{\beta,i} = c_{\beta,i} + O(|x|^{\varrho_i}) \quad \text{as } |x| \rightarrow +\infty.$$

The gradient estimates in (2.37) are consequences of Corollary 2.1, which ends the proof.  $\square$

**Corollary 2.3** *Under the assumptions of Theorem 2.1 the solutions  $v_{\beta,i}$  satisfy the flux identity*

$$\int_{\mathbb{R}^2} W F_i(\lambda^\beta e^{v_{\beta,i}}) dx = 2\pi(2(N - M) + \beta). \quad (2.46)$$

**Proof.** For any  $R > 0$ , there holds

$$-\int_{|x|=R} \frac{\partial v_{\beta,i}}{\partial r} dS + \int_{B_R} W F_i(\lambda e^{v_{\beta,i}}) dx = \int_{B_R} g_\beta dx.$$

By (2.37),

$$\left| \int_{|x|=R} \frac{\partial v_{\beta,i}}{\partial r} dS \right| = O(|x|^{\rho_i}) \quad \text{as } |x| \rightarrow +\infty,$$

where  $\rho_i$  is defined in (2.44). The result follows from (2.35).  $\square$

For the critical case  $\beta = \beta^* := 2aN - 2$  where  $a > 0$  and  $0 < aN \leq 1$ , the problem related to (1.1) is following

$$-\Delta u + W F_2(\lambda^{\beta^*} \Lambda^{-2} e^u) = g_{\beta^*} \quad \text{in } \mathbb{R}^2, \quad (2.47)$$

where

$$g_{\beta^*} = f_1 - f_2 + \beta^* \Delta \ln \lambda - 2\Delta \ln \Lambda, \quad (2.48)$$

is subject to

$$\int_{\mathbb{R}^2} g_{\beta^*} dx = 2\pi[2(N - M) + \beta^*]$$

and  $W$  satisfies that

$(\mathcal{W}_1)$  *The function  $W$  is positive and Hölder continuous locally in  $\mathbb{R}^2 \setminus \Sigma_1$  and*

$$W(x) \leq c_{13}|x - p_j|^{-2n_j a} \quad \text{in } B_\sigma(p_j) \quad \text{and} \quad \limsup_{|x| \rightarrow \infty} (|x|^{2aN} W(x) - 2|x|) < +\infty,$$

where  $c_{13} > 0$ ,  $n_j a < 1$  with  $j = 1, \dots, k$ .

**Theorem 2.2** *Let  $F_2(s) = \frac{s}{e^{\nu_1 - \nu_2 + s}}$ ,  $g_{\beta^*}$  be defined in (2.48) with  $\beta^* = 2(aN - 1) \leq 0$  and  $W$  satisfies  $(\mathcal{W}_1)$ . Assume furthermore that  $M < (1 + a)N - 1$  and set  $\theta^* = \min\{3, 2 - \beta^*\} \geq 2$ . Then problem (2.47) has a unique bounded solution  $v$  and there exists  $c_* \in \mathbb{R}$  such that*

$$\begin{aligned} v_*(x) &= c_* + O(|x|^{-\frac{\theta^* - 2}{\theta^* - 1}}) & \text{as } |x| \rightarrow +\infty \\ |\nabla v(x)| &= O(|x|^{-1 - \frac{\theta^* - 2}{\theta^* - 1}}) & \text{as } |x| \rightarrow +\infty, \end{aligned} \quad (2.49)$$

if  $aN < 1$ , or

$$\begin{aligned} v_*(x) &= c_* + O((\ln |x|)^{-4}) & \text{as } |x| \rightarrow +\infty \\ |\nabla v(x)| &= O(|x|^{-1} (\ln |x|)^{-4}) & \text{as } |x| \rightarrow +\infty, \end{aligned} \quad (2.50)$$

if  $aN = 1$ .

**Proof.** Notice that the assumptions  $aN \leq 1$  and  $M < (1 + a)N - 1$  imply  $N - M > 0$ . Set

$$\Lambda_0(x) = \frac{1}{1 + |x|^2} \quad \text{for any } x \in \mathbb{R}^2, \quad (2.51)$$

and for  $t \in \mathbb{R}$ ,

$$h_t(x) = \frac{W\lambda^{\beta^*}\Lambda^{-2}e^{t\Lambda_0(x)}}{e^{\nu_1(x)-\nu_2(x)} + \lambda^{\beta^*}\Lambda^{-2}e^{t\Lambda_0(x)}} \quad \text{for any } x \in \mathbb{R}^2 \setminus \Sigma$$

with  $h_t(x) = 0$  for  $x \in \Sigma_2$ . The function  $h_t(\cdot)$  is continuous in  $\mathbb{R}^2 \setminus \Sigma_1$  and  $t \mapsto h_t(x)$  is increasing for all  $x \in \mathbb{R}^2 \setminus \Sigma$ . Direct computation implies the following properties:

$$h_t(x) \rightarrow W \quad \text{locally in } \mathbb{R}^2 \setminus \Sigma_2 \quad \text{as } t \rightarrow +\infty$$

and

$$h_t(x) \rightarrow 0 \quad \text{locally in } \mathbb{R}^2 \setminus \Sigma_1 \quad \text{as } t \rightarrow -\infty.$$

Since  $2aN \leq 2$ , there holds

$$\int_{\mathbb{R}^2} W(x)dx = \infty.$$

Furthermore, there exist  $\tau \in \mathbb{R}$  and  $r_* > 0$  such that for any  $t \leq \tau$  and  $|x| \geq r_*$ ,

$$h_t(x) \leq c_{14} \frac{|x|^{-2}(\ln(|x| + 1))^{-2}}{1 + |x|^{2aN-2}(\ln(|x| + 1))^{-2}},$$

where  $c_{14} > 0$  depends on  $\tau$ . Since  $2aN - 2 \leq 0$ , it follows that for  $|x| \geq r_*$

$$h_t(x) \leq c_{15}|x|^{-2}(\ln(|x| + 1))^{-2}. \quad (2.52)$$

Hence, by the dominated convergence theorem,

$$\lim_{t \rightarrow -\infty} \int_{\mathbb{R}^2} h_t(x)dx = 0.$$

Using the fact that  $t \mapsto \int_{\mathbb{R}^2} h_t(x)dx$  is increasing, there exists  $t_0 \in \mathbb{R}$  such that

$$\int_{\mathbb{R}^2} h_{t_0}(x)dx = 2\pi[2(N - M) + \beta^*] = \int_{\mathbb{R}^2} g_{\beta^*}(x)dx. \quad (2.53)$$

We claim that

$$|w_0(x)| \leq c_{16}|x|^{-\frac{\theta^*-2}{\theta^*-1}} \quad \text{for } |x| \text{ large enough,} \quad (2.54)$$

and if this holds true it will follow that  $\|w_0\|_{L^\infty} < \infty$ , where  $w_0 = \Gamma * (g_{\beta^*} - h_{t_0})$ .

Using (2.48),

$$g_{\beta^*}(x) = \frac{2}{|x|^2\Lambda^2(x)} \quad \text{for } |x| \geq r_1$$

and

$$h_{t_0}(x) = \frac{W\lambda^{\beta^*}\Lambda^{-2}e^{t_0\Lambda_0}}{1 + \lambda^{\beta^*}\Lambda^{-2}e^{t_0\Lambda_0}} = \frac{2|x|^{-2}e^{t_0\Lambda_0}(1 + O(|x|^{-1}))}{\Lambda^2 + |x|^{\beta^*}e^{t_0\Lambda_0}} \quad \text{as } |x| \rightarrow +\infty.$$

Therefore, we obtain that

$$\begin{aligned} g_{\beta^*} - h_{t_0} &= \frac{2e^{t_0\Lambda_0}}{|x|^2} \left( \frac{\Lambda^2 e^{t_0\Lambda_0} (1 + O(|x|^{-1})) - \Lambda^2 - |x|^{\beta^*} e^{t_0\Lambda_0}}{\Lambda^2 e^{t_0\Lambda_0} (\Lambda^2 + |x|^{\beta^*} e^{t_0\Lambda_0})} \right) \\ &= \frac{2e^{t_0\Lambda_0}}{|x|^2 \Lambda^2 e^{t_0\Lambda_0} (\Lambda^2 + |x|^{\beta^*} e^{t_0\Lambda_0})} \left( \Lambda^2 (e^{t_0\Lambda_0} - 1) - e^{t_0\Lambda_0} (|x|^{\beta^*} - \Lambda^2 O(|x|^{-1})) \right). \end{aligned} \quad (2.55)$$

Since  $\Lambda_0(x)$  is defined by (2.51),  $e^{t_0\Lambda_0} - 1 = O(|x|^{-2})$  at infinity. Noticing that  $\beta^* = 0$  if  $aN = 1$ , we obtain

$$|g_{\beta^*} - h_{t_0}| \leq c_{17} \max \left\{ |x|^{-3} \Lambda^{-2}, |x|^{-2+\beta^*} \Lambda^{-4} \right\} \leq c_{17} \begin{cases} |x|^{-\theta^*} & \text{if } aN < 1 \\ |x|^{-2} (\ln |x|)^{-4} & \text{if } aN = 1. \end{cases} \quad (2.56)$$

Additionally,  $\int_{\mathbb{R}^2} w_0 dx = 0$ . Therefore, from Lemma 2.2 and Lemmas 2.3, that  $w_0$  remains bounded on  $\mathbb{R}^2$  and that there holds

$$|w_0(x)| \leq c_{18} (1 + |x|)^{-\frac{\theta^*-2}{\theta^*-1}} \quad \text{for all } x \in \mathbb{R}^2 \quad \text{if } aN < 1 \quad (2.57)$$

and

$$|w_0(x)| \leq c_{18} (\ln(2 + |x|))^{-4} \quad \text{for all } x \in \mathbb{R}^2 \quad \text{if } aN = 1. \quad (2.58)$$

*Existence.* We first construct a supersolution.

$$\bar{v} = (t_0)_+ + w_0 + \|w_0\|_{L^\infty(\mathbb{R}^2)} \quad \text{in } \mathbb{R}^2.$$

Since  $\Lambda_0 : \mathbb{R}^2 \rightarrow (0, 1]$ , then  $\bar{v} \geq t_0 \Lambda_0$  in  $\mathbb{R}^2$ . The function  $t \mapsto \frac{\Lambda^{-2} e^t}{e^{\nu_1 - \nu_2} + \Lambda^{-2} e^t}$  is increasing, therefore,

$$\frac{W \lambda^{\beta^*} \Lambda^{-2} e^{\bar{v}}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{\bar{v}}} \geq \frac{W \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}},$$

which implies,

$$-\Delta \bar{v} + \frac{W \lambda^{\beta^*} \Lambda^{-2} e^{\bar{v}}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{\bar{v}}} - g_{\beta^*} \geq g_{\beta^*} - h_{t_0} + \frac{W \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}} - g_{\beta^*} = 0,$$

then  $\bar{v}$  is a super solution of (2.33).

Similarly we construct a subsolution by setting  $\underline{v} = (t_0)_- + w_0 - \|w_0\|_{L^\infty(\mathbb{R}^2)}$ . Using  $\underline{v} \leq t_0 \Lambda_0$  in  $\mathbb{R}^2$  and by monotonicity, we have that

$$\frac{W \lambda^{\beta^*} \Lambda^{-2} e^{\underline{v}}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{\underline{v}}} \leq \frac{W \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}},$$

thus,

$$-\Delta \underline{v} + \frac{W \lambda^{\beta^*} \Lambda^{-2} e^{\underline{v}}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{\underline{v}}} - g_{\beta^*} \leq g_{\beta^*} - h_{t_0} + \frac{W \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^{t_0 \Lambda_0}} - g_{\beta^*} = 0,$$



thus  $\underline{v}$  is a subsolution.

Since  $\bar{v} > \underline{v}$ , the standard iterative process, yields the existence of a solution  $v_*$  of (2.33) such that

$$\underline{v} \leq v_* \leq \bar{v} \quad \text{in } \mathbb{R}^2.$$

As in the proof of Theorem 2.1 the solutions are unique in the class of bounded solutions, a class to which  $v_*$  belongs. Put  $\Phi_* = g_{\beta^*} - WF_2(\lambda^* \Lambda^{-2} e^{v_*})$ , then  $w_* = v_* - \Gamma * \Phi_*$  is harmonic and bounded, hence it is a constant, say  $c_*$ . Since  $\Phi_*$  satisfies the same estimate (2.57), with being another constant, we deduce from Lemma 2.2 that for all  $x \in \mathbb{R}^2$

$$|\Gamma * \Phi_*| \leq c_{19} \begin{cases} (1 + |x|)^{-\frac{\theta^* - 2}{\theta^* - 1}} & \text{if } aN < 1 \\ (1 + |x|)^{-2} (\ln(2 + |x|))^{-4} & \text{if } aN = 1. \end{cases} \quad (2.59)$$

This implies inequalities (2.49) and (2.50) by Lemma 2.2 and Lemma 2.3 and Corollary 2.1 and Corollary 2.2.  $\square$

Similarly as Corollary 2.3, there holds

**Corollary 2.4** *Under the assumptions of Theorem 2.2 the solutions  $v_{\beta^*}$  satisfy*

$$\int_{\mathbb{R}^2} WF_2(\lambda^{\beta^*} \Lambda^{-2} e^{v_{\beta^*}}) dx = 2\pi(2(N - M) + \beta^*). \quad (2.60)$$

From the existence and uniqueness of solutions of (2.33) and (2.47), it is easy to prove the following statements.

**Corollary 2.5** *Under the assumptions of Theorem 2.1, if  $\bar{w}_i$  and  $\underline{w}_i$  are respectively a bounded supersolution and a bounded subsolution of (2.33) such that  $\underline{w}_i \leq \bar{w}_i$ , then the standard iterative process will converges to the unique bounded solution  $v_i$  of (2.33), and  $\underline{w}_i \leq v_i \leq \bar{w}_i$ . A similar result holds concerning equation (2.47) under the assumption of Theorem 2.1.*

**Corollary 2.6** *Under the assumptions of Theorem 2.2, the function  $w_* := \lambda^{\beta^*} \Lambda^{-2} + v_*$  where  $v_*$  is the unique bounded solution of (2.47) satisfies*

$$-\Delta w_* + WF_2(e^{w_*}) = f_1 - f_2 \quad \text{in } \mathbb{R}^2. \quad (2.61)$$

### 3 Minimal solution

In order to consider solutions  $w$  of (2.3) with asymptotic behaviors  $\beta \ln |x| + O(1)$ , we look for  $w$  under the form  $w = \beta \ln |x| + v$  where  $v$  is a bounded function satisfying some related equation. In particular, the non-topological solution  $u_\beta$  of problem (1.1) is looked for under the form

$$u_\beta = -\nu_1 + \nu_2 + \beta \ln \lambda + v_\beta \quad \text{or} \quad w_\beta = v_\beta + \beta \ln \lambda,$$

where  $\lambda$  is given by (2.30) and  $v_\beta$  is a bounded classical solution of

$$-\Delta v + \frac{V \lambda^\beta e^v}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^v)^{1+a}} = g_\beta \quad \text{in } \mathbb{R}^2 \quad (3.1)$$

with  $V$  being defined in (2.4). Here and in what follows, we always assume that  $a = 16\pi G$ ,  $an_j < 1$  for  $j = 1, \dots, k$  and  $\mathcal{M}$  is the total magnetic flux given in (1.9).

We first consider the non-topological solutions of type I for problem (1.1) in the subcritical case, which are solutions verifying  $u(x) = \beta \ln |x| + O(1)$  as  $|x| \rightarrow \infty$  with  $\beta < 0$ . It is equivalent to look for classical solutions of (3.1) with  $\beta < 0$ .

**Proposition 3.1** *Let  $N, M$  be positive integers verifying (1.12) and  $aN \leq 1$ , then for any  $\beta \in (-2(N - M), \beta^*)$ , problem (3.1) has a minimal bounded solution  $v_{\beta, \min}$  such that*

$$\int_{\mathbb{R}^2} V \frac{\lambda^\beta e^{v_{\beta, \min}}}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_{\beta, \min}})^{1+a}} dx = 2\pi(2(N - M) + \beta). \quad (3.2)$$

**Proof.** *Step 1: construction of an approximating scheme.* We recall that

$$\mathbf{P} = \frac{V}{e^{a(\nu_1 - \nu_2)}} \quad \text{in } \mathbb{R}^2 \setminus \Sigma,$$

then

$$\lim_{x \rightarrow p_j} \mathbf{P}(x) |x - p_j|^{2n_j a} = A_0 \prod_{i \neq j}^k |p_i - p_j|^{-2an_i}, \quad \lim_{|x - q_j| \rightarrow 0^+} \mathbf{P}(x) = 0,$$

and

$$\lim_{|x| \rightarrow \infty} \mathbf{P}(x) |x|^{2aN} = A_0. \quad (3.3)$$

Since  $aN \leq 1$ , there holds

$$\int_{\mathbb{R}^2} \mathbf{P}(x) dx = \infty,$$

so that  $\mathbf{P}$  verifies the assumption  $(\mathcal{W}_0)$  with  $\tau_{p_j} = 2n_j a < 2$  and  $\tau_\infty = 2aN > 2 - 2(N - M)$ . Theorem 2.1-(ii) implies that for any  $\beta \in (-2(N - M), 2aN - 2)$ , the nonlinear elliptic problem

$$-\Delta v + \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{\lambda^\beta e^v}{e^{\nu_1 - \nu_2} + \lambda^\beta e^v} = g_\beta \quad \text{in } \mathbb{R}^2 \quad (3.4)$$

has a unique bounded solution  $v_0$ , which is continuous in  $\mathbb{R}^2$ , smooth in  $\mathbb{R}^2 \setminus \Sigma$  and

$$\int_{\mathbb{R}^2} \left( \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{\lambda^\beta e^{v_0}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_0}} - g_\beta \right) dx = 0$$

by the same argument as in Theorem 2.1-(ii), then there exists a constant  $c_{0, \beta}$  such that

$$\lim_{|x| \rightarrow +\infty} v_0(x) = c_{0, \beta} \quad \text{and} \quad v_0(x) - c_{0, \beta} = O\left(|x|^{-\frac{2aN - \beta - 2}{2aN - \beta - 1}}\right) \quad \text{as } |x| \rightarrow +\infty. \quad (3.5)$$

We set

$$W_0 = \mathbf{P} \quad \text{and} \quad W_1 = \frac{V}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_0})^a} = \frac{e^{a(\nu_1 - \nu_2)}}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_0})^a} W_0 \quad \text{in } \mathbb{R}^2 \setminus \Sigma.$$

The function  $W_1$  is positive and Hölder continuous in  $\mathbb{R}^2 \setminus \Sigma_1$ , and since

$$0 < W_1(x) \leq W_0(x) \quad \forall x \in \mathbb{R}^2, \quad (3.6)$$

it satisfies  $W_0$ . Furthermore, as  $N - M > 0$ ,  $v_0(x) \rightarrow 0$  as  $|x| \rightarrow \infty$  and  $\beta < 0$  and therefore  $W_1(x) = W_0(x)(1 + o(1))$  as  $|x| \rightarrow \infty$ . Applying Theorem 2.1-(ii), with  $\gamma_\infty = 2aN$ , we see that there exists a unique bounded function  $v_1$  satisfying

$$-\Delta v_1 + W_1 \frac{\lambda^\beta e^{v_1}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1}} = g_\beta \quad \text{in } \mathbb{R}^2. \quad (3.7)$$

Furthermore,  $v_1(x)$  converges to some constant  $c_{1,\beta}$  when  $x \rightarrow +\infty$  and

$$v_1(x) = c_{1,\beta} + O\left(|x|^{-\frac{2aN - \beta - 2}{2aN - \beta - 1}}\right) \quad \text{as } |x| \rightarrow +\infty. \quad (3.8)$$

Set  $z = v_0 - v_1$ . Since the function  $t \mapsto \frac{\lambda^\beta e^t}{e^{\nu_1 - \nu_2} + \lambda^\beta e^t}$  is nondecreasing, it follows that

$$\begin{aligned} -\Delta z_+^2 &= 2z_+(W_1 - W_0) \frac{\lambda^\beta e^{v_1}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1}} - 2W_0 z_+ \left( \frac{\lambda^\beta e^{v_0}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_0}} - \frac{\lambda^\beta e^{v_1}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1}} \right) - 2|\nabla z_+|^2 \\ &\leq 0. \end{aligned}$$

Hence  $z_+^2$  is subharmonic and bounded, it is therefore constant. Hence  $(v_0 - v_1)_+ = c \geq 0$ . If  $c > 0$  then  $\sup\{v_0 - v_1, 0\} = c$ , which implies that  $v_0 - v_1 = c$ . Replacing  $v_0$  by  $v_1 + c$  we deduce from (3.5), (3.7)

$$\frac{V}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1 + c})^a} \frac{\lambda^\beta e^{v_1}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1}} = \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{\lambda^\beta e^{v_1 + c}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1 + c}},$$

which yields

$$e^c \left( e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1} \right) = e^{a(\nu_1 - \nu_2)} \left( e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_1 + c} \right)^{1-a} \quad \text{in } \mathbb{R}^2 \setminus \Sigma.$$

Since  $\beta < 0$ , we obtain  $e^c = 1$  by letting  $|x| \rightarrow \infty$ . Hence  $c = 0$  which implies  $v_0 \leq v_1$  in  $\mathbb{R}^2$  and  $c_{1,\beta} \geq c_{0,\beta}$ .

By induction, we suppose that for  $n \geq 2$  we have constructed the sequences  $\{v_k\}_{k < n}$  of bounded solutions to

$$-\Delta v_k + W_k \frac{\lambda^\beta e^{v_k}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_k}} = g_\beta \quad \text{in } \mathbb{R}^2, \quad (3.9)$$

where

$$W_k = \frac{e^{a(\nu_1 - \nu_2)}}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_{k-1}})^a} W_0.$$

Then  $0 < W_k \leq W_{k-1} \leq \dots \leq W_0$  and therefore  $v_0 \leq \dots \leq v_{k-1} \leq v_k$ , and furthermore

$$v_k(x) = c_{k,\beta} + O\left(|x|^{-\frac{2aN - \beta - 2}{2aN - \beta - 1}}\right) \quad \text{as } |x| \rightarrow +\infty. \quad (3.10)$$

Then  $v_n$  is the unique bounded solutions of

$$-\Delta v_n + W_n \frac{\lambda^\beta e^{v_n}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_n}} = g_\beta \quad \text{in } \mathbb{R}^2, \quad (3.11)$$

where

$$W_n = \frac{e^{a(\nu_1 - \nu_2)}}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_{n-1}})^a} W_0 \leq W_{n-1} = \frac{e^{a(\nu_1 - \nu_2)}}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_{n-2}})^a} W_0,$$

since  $v_{n-2} \leq v_{n-1}$  by induction. Furthermore, by Lemma 2.2 (since  $\beta < 0$  and  $N - M > 0$ ),

$$v_n(x) = c_{n,\beta} + O\left(|x|^{-\frac{2aN - \beta - 2}{2aN - \beta - 1}}\right) \quad \text{as } |x| \rightarrow +\infty. \quad (3.12)$$

As above the function  $(v_{n-1} - v_n)_+^2$  is subharmonic and bounded, hence constant which implies  $v_{n-1} = v_n + c$ ,  $c \geq 0$ . If  $c > 0$ , then from the equations satisfied by  $v_n$  and  $v_{n-1}$ ,

$$\frac{e^c}{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_{n-2}})^a} = \frac{(e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_n + c})^{1-a}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_n}} \quad \text{in } \mathbb{R}^2 \setminus \Sigma.$$

Approaching  $|x| \rightarrow \infty$  yields  $e^c = 1$  and finally  $v_{n-1} \leq v_n$  and  $n \mapsto c_{n,\beta}$  is increasing.

Let  $R > 1$  such that  $\text{supp}(g_\beta) \subset B_R$  and  $\Theta(x) := \Gamma * |g_\beta|(x) = \frac{1}{2\pi} \int_{B_R} |g_\beta(x)| \ln |x - y| dy$ . For  $|x| \geq R+1$ , one has  $1 \leq |x - y| \leq |x| + R$ , hence  $0 \leq \ln |x - y| \leq \ln(|x| + R) \leq \ln |x| + \frac{R}{|x|} \leq \ln |x| + 1$ , therefore

$$0 \leq \Theta(x) \leq \frac{R^2 \|g_\beta\|_{L^\infty}}{2} (\ln |x| + 1) \quad \text{if } |x| \geq R + 1.$$

Since  $|\Theta|$  is bounded by some  $c_{20}$  on  $B_{R+1}$ , we deduce

$$|\Theta(x)| \leq c_{20} + \frac{R^2 \|g_\beta\|_{L^\infty}}{2} (\ln_+ |x| + 1) \quad \text{for all } x \in \mathbb{R}^2. \quad (3.13)$$

Set  $z = v_n - \Theta$ , then

$$-\Delta z_+^2 \leq -2z_+ \Delta z = -2z_+ W_n \frac{\lambda^\beta e^{v_n}}{e^{\nu_1 - \nu_2} + \lambda^\beta e^{v_n}} \leq 0.$$

The function  $z_+$  has compact support because of (3.13). It is subharmonic, nonnegative and bounded, hence it is constant with value zero necessarily, hence, for any  $n \in \mathbb{N}$ ,

$$v_0(x) \leq v_n(x) \leq c_{20} + \frac{R^2 \|g_\beta\|_{L^\infty}}{2} (\ln_+ |x| + 1) \quad \text{for all } x \in \mathbb{R}^2. \quad (3.14)$$

For  $\epsilon > 0$  set

$$w_\epsilon(x) = \epsilon \ln |x| + c_{20} + \frac{R^2 \|g_\beta\|_{L^\infty}}{2} (\ln R + 1).$$

Then  $w_\epsilon$  is harmonic in  $\overline{B_R^c}$ . It is larger than  $v_n$  for  $|x| = R$  and at infinity, since  $v_n$  is bounded. If we set  $Z = v_n - w_\epsilon$ , then as above the function  $Z_+^2$  is subharmonic, nonnegative and bounded in  $B_R^c$ . Since it vanishes for  $|x| = R$ , its extension  $\zeta$  by 0 in  $\overline{B_R}$  is still subharmonic nonnegative

and bounded. It is therefore constant. Since it vanishes at infinity, it is identically 0. Hence  $v_n - w_\epsilon \leq 0$ . Letting  $\epsilon \rightarrow 0$  we infer

$$v_0(x) \leq v_n(x) \leq c_{20} + \frac{R^2 \|g_\beta\|_{L^\infty}}{2} (\ln R + 1) \quad \text{for all } x \in \mathbb{R}^2. \quad (3.15)$$

Combining Lemma 2.2 with (3.15) for  $n = 1$  we infer

$$|v_n(x) - c_{n,\beta}| \leq c_{23}(1 + |x|)^{-\frac{2aN-\beta-2}{2aN-\beta-1}} \quad \text{for all } x \in \mathbb{R}^2, \quad (3.16)$$

where  $c_{23} > 0$  is independent of  $n$ . By Lemma 2.2

$$|\nabla v_n(x)| \leq c_{24}|x|^{-1-\frac{2aN-\beta-2}{2aN-\beta-1}} \quad \text{for } |x| \text{ large enough,} \quad (3.17)$$

then,

$$-\int_{|x|=R} \frac{\partial v_n}{\partial r} dS + \int_{B_R} W_n \frac{\lambda^\beta e^{v_n}}{e^{\nu_1-\nu_2} + \lambda^\beta e^{v_n}} dx = \int_{B_R} g_\beta dx.$$

By (3.17), the first integral tends to 0 when  $R \rightarrow +\infty$ , therefore

$$\int_{\mathbb{R}^2} W_n \frac{\lambda^\beta e^{v_n}}{e^{\nu_1-\nu_2} + \lambda^\beta e^{v_n}} dx = \int_{\mathbb{R}^2} g_\beta dx = 2\pi(2(N-M) + \beta). \quad (3.18)$$

Set  $v_{\beta,min} = \lim_{n \rightarrow \infty} v_n$  and  $c_\beta = \lim_{n \rightarrow \infty} c_{n,\beta}$ , then

$$W_n \rightarrow W_\infty := \frac{e^{a(\nu_1-\nu_2)}}{(e^{\nu_1-\nu_2} + \lambda^\beta e^{v_{\beta,min}})^a} W_0$$

and

$$|v_{\beta,min}(x) - c_\beta| \leq c_{23}(1 + |x|)^{-\frac{2aN+2(N-M)-\beta-2}{2aN+2(N-M)-\beta-1}} \quad \text{for all } x \in \mathbb{R}^2. \quad (3.19)$$

Furthermore

$$0 \leq W_n \frac{\lambda^\beta e^{v_n}}{e^{\nu_1-\nu_2} + \lambda^\beta e^{v_n}} \leq W_0 \frac{\lambda^\beta e^{v_{\beta,min}}}{e^{\nu_1-\nu_2} + \lambda^\beta e^{v_{\beta,min}}}.$$

The right-hand side of the above inequality is an integrable function, therefore

$$W_n \frac{\lambda^\beta e^{v_n}}{e^{\nu_1-\nu_2} + \lambda^\beta e^{v_n}} \rightarrow W_0 \frac{e^{a(\nu_1-\nu_2)} \lambda^\beta e^{v_{\beta,min}}}{(e^{\nu_1-\nu_2} + \lambda^\beta e^{v_{\beta,min}})^{1+a}} \quad \text{in } L^1(\mathbb{R}^2) \quad \text{as } n \rightarrow +\infty.$$

This implies that  $v_{\beta,min}$  is a weak solution of (1.1) and relation (3.2) holds.

*Step 2:  $v_{\beta,min}$  is minimal among the bounded solutions.* Let  $\tilde{v}$  be any bounded solution. Then  $\frac{V}{(e^{\nu_1-\nu_2} + \lambda^\beta e^{\tilde{v}})^a} \leq \frac{V}{e^{a(\nu_1-\nu_2)}}$ , and by uniqueness, it implies  $v_0 \leq \tilde{v}$ . Hence  $\frac{V}{(e^{\nu_1-\nu_2} + \lambda^\beta e^{\tilde{v}})^a} \leq \frac{V}{(e^{\nu_1-\nu_2} + \lambda^\beta e^{v_0})^a}$  and therefore  $v_1 \leq \tilde{v}$ . By induction we obtain  $v_n \leq \tilde{v}$  and finally  $v_{\beta,min} \leq \tilde{v}$ .

*Step 3: asymptotic behaviour.* Put

$$F = g_\beta - \frac{V \lambda^\beta e^{v_{\beta,min}}}{(e^{\nu_1-\nu_2} + \lambda^\beta e^{v_{\beta,min}})^{1+a}}.$$

Then  $\int_{\mathbb{R}^2} F dx = 0$  and  $|F(x)| \leq c_{21}|x|^{-(2aN-\beta)}$  for  $|x| \geq r_0$ . So we have (3.2) and applying Lemma 2.2 implies that

$$|\Gamma * F| \leq c_{23}(1 + |x|)^{-\frac{2aN-\beta-2}{2aN-\beta-1}} \quad \text{for all } x \in \mathbb{R}^2.$$

Therefore  $w = v_{\beta, \min} - \Gamma * F$  is harmonic and bounded in  $\mathbb{R}^2$ . It is therefore constant. This implies

$$v_{\beta, \min} = c_\beta + O(|x|^{-\frac{2aN-\beta-2}{2aN-\beta-1}}) \quad \text{as } |x| \rightarrow +\infty. \quad (3.20)$$

We complete the proof.  $\square$

**Proof of Theorem 1.2 part (i).** Let

$$u_{\beta, \min} = -\nu_1 + \nu_2 + \beta \ln \lambda + v_{\beta, \min},$$

where  $v_{\beta, \min}$  is the minimal bounded solution of (3.1) obtained in Proposition 3.1. Then  $u_{\beta, \min}$  is the minimal non-topological solution of type I of (1.1) in the sense that

$$u_{\beta, \min}(x) - \beta \ln |x| = O(1) \quad \text{as } |x| \rightarrow +\infty.$$

Moreover,  $u_{\beta, \min}$  verifies (1.13) and its total magnetic flux is  $2\pi[2(N - M) + \beta]$  by (3.2).  $\square$

## 4 Critical-minimal solutions

### 4.1 Non-topological solutions

If  $N > M$  and  $aN < 1$ , we recall that by Theorem 2.1, for any  $\beta \in (-2(N - M), \beta^*)$ , with  $\beta^* = 2(aN - 1) < 0$ , there exists a unique bounded solution  $v_\beta$  to

$$-\Delta v + \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{\lambda^\beta e^v}{e^{\nu_1 - \nu_2} + \lambda^\beta e^v} = g_\beta \quad \text{in } \mathbb{R}^2 \quad (4.1)$$

and by Theorem 2.2, there exists a unique bounded solution  $v_{\beta^*}$  to

$$-\Delta v + \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{\lambda^{\beta^*} \Lambda^{-2} e^v}{e^{\nu_1 - \nu_2} + \lambda^{\beta^*} \Lambda^{-2} e^v} = g_{\beta^*} \quad \text{in } \mathbb{R}^2. \quad (4.2)$$

For  $\beta \in (-2(N - M), \beta^*)$ , we first set

$$w_\beta = v_\beta + \beta \ln \lambda, \quad (4.3)$$

then  $w_\beta$  is the unique solution of

$$-\Delta w + \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{e^w}{e^{\nu_1 - \nu_2} + e^w} = f_1 - f_2 \quad \text{in } \mathbb{R}^2 \quad (4.4)$$

such that  $w - \beta \ln \lambda$  is bounded in  $\mathbb{R}^2$ .

When  $\beta = \beta^*$ , we set

$$w_{\beta^*} = v_{\beta^*} + \beta^* \ln \lambda - 2 \ln \Lambda, \quad (4.5)$$

and then  $w_{\beta^*}$  is the unique solution of (4.4) such that  $w - \beta^* \ln \lambda - 2 \ln \Lambda$  remains bounded in  $\mathbb{R}^2$ .

**Proposition 4.1** *Under the assumptions of Theorem 2.2, the mapping  $\beta \mapsto w_\beta$  is increasing for  $\beta \in (-2(N - M), \beta^*)$  and*

$$w_{\beta^*} = \sup \{w_\beta \text{ in } \mathbb{R}^2 : \beta \in (-2(N - M), \beta^*)\}.$$

**Proof.** If  $\beta^* > \beta > \beta' > -2(N - M)$ , the function  $z = w_{\beta'} - w_\beta$  is negative in  $B_R^c$  for some  $R > 0$ . Hence

$$-\Delta z_+^2 = -2z_+\Delta z - 2|\nabla z_+|^2 \leq -\frac{2V}{e^{a(\nu_1-\nu_2)}} \left( \frac{e_{\beta'}^w}{e^{\nu_1-\nu_2} + e^{w_{\beta'}}} - \frac{e_\beta^w}{e^{\nu_1-\nu_2} + e^{w_\beta}} \right) (w_{\beta'} - w_\beta) \leq 0.$$

Hence  $z_+^2$  is a nonnegative and bounded subharmonic function in  $\mathbb{R}^2$ , it is therefore constant. Since it vanishes in  $B_R^c$ , it is identically 0, which yields  $w_{\beta'} \leq w_\beta$ . Actually the inequality is strict since it is strict at infinity and there cannot exist  $x_0 \in \mathbb{R}^2$  such that  $w_{\beta'}(x_0) = w_\beta(x_0)$  because of the strong maximum principle. Similarly, if  $\beta < \beta^*$ , there holds by (4.3) and (4.5)

$$(w_\beta - w_{\beta^*})(x) = (\beta - \beta^*) \ln |x| + 2 \ln(\ln |x|) + O(1) \quad \text{as } |x| \rightarrow +\infty.$$

Hence  $z_+^2 = (w_\beta - w_{\beta^*})_+^2$  is subharmonic nonnegative and bounded, hence constant and finally zero. Therefore  $w_\beta \leq w_{\beta^*}$ , and actually  $w_\beta < w_{\beta^*}$  by the strong maximum principle. We set

$$\tilde{w}_{\beta^*} := \sup \{w_\beta : \beta \in (-2(N - M), \beta^*)\} = \lim_{\beta \uparrow \beta^*} w_\beta.$$

Then  $\tilde{w}_{\beta^*} \leq w_{\beta^*}$  and  $w_{\beta^*}$  is a solution of (4.4). By the strong maximum principle, either  $\tilde{w}_{\beta^*} < w_{\beta^*}$  or  $\tilde{w}_{\beta^*} = w_{\beta^*}$ . In order to identify  $w_{\beta^*}$ , we use the flux identities obtained in Corollaries 2.3 and 2.4, replacing  $v_{\beta,2}$  and  $v_{\beta^*}$  by their expressions in (4.3) and (4.5):

$$\mathcal{M}(w_\beta) = \int_{\mathbb{R}^2} \frac{V}{e^{\nu_1-\nu_2}} \frac{e^{w_\beta}}{e^{\nu_1-\nu_2} + e^{w_\beta}} = 2\pi(2(N - M) + \beta)$$

and

$$\mathcal{M}(w_{\beta^*}) = \int_{\mathbb{R}^2} \frac{V}{e^{\nu_1-\nu_2}} \frac{e^{w_{\beta^*}}}{e^{\nu_1-\nu_2} + e^{w_{\beta^*}}} dx = 2\pi(2(N - M) + \beta^*).$$

Since the mapping  $\beta \mapsto \frac{e^{w_\beta}}{1+e^{w_\beta}}$  is increasing, there holds by the monotone convergence theorem,

$$\begin{aligned} \mathcal{M}(\tilde{w}_{\beta^*}) &= \int_{\mathbb{R}^2} \frac{V}{e^{a(\nu_1-\nu_2)}} \frac{e^{\tilde{w}_{\beta^*}}}{e^{\nu_1-\nu_2} + e^{\tilde{w}_{\beta^*}}} dx \\ &= \lim_{\beta \uparrow \beta^*} \int_{\mathbb{R}^2} \frac{V}{e^{a(\nu_1-\nu_2)}} \frac{e^{w_\beta}}{e^{\nu_1-\nu_2} + e^{w_\beta}} dx \\ &= 2\pi(2(N - M) + \beta^*) \\ &= \int_{\mathbb{R}^2} \frac{V}{e^{a(\nu_1-\nu_2)}} \frac{e^{w_{\beta^*}}}{e^{\nu_1-\nu_2} + e^{w_{\beta^*}}} dx, \end{aligned} \tag{4.6}$$

where  $\frac{e^{\tilde{w}_{\beta^*}}}{e^{\nu_1-\nu_2} + e^{\tilde{w}_{\beta^*}}} \leq \frac{e^{w_{\beta^*}}}{e^{\nu_1-\nu_2} + e^{w_{\beta^*}}}$ . Then it implies that  $\tilde{w}_{\beta^*} = w_{\beta^*}$  almost everywhere and actually everywhere by continuity.  $\square$

## 4.2 Proof of Theorem 1.3

If  $v_{\beta,min}$  is the minimal bounded solution of (3.1) obtained in Proposition 3.1, we set

$$w_{\beta,min} = v_{\beta,min} + \beta \ln \lambda \quad \text{in } \mathbb{R}^2. \quad (4.7)$$

Then  $w_{\beta,min}$  is a solution of

$$\begin{cases} -\Delta w + \frac{Ve^w}{(e^{\nu_1-\nu_2} + e^w)^{1+a}} = f_1 - f_2 & \text{in } \mathbb{R}^2, \\ w = \beta \ln \lambda + O(1) & \text{as } |x| \rightarrow +\infty. \end{cases} \quad (4.8)$$

Since  $v_{\beta,min}$  is the minimal bounded solution of (3.1),  $w_{\beta,min}$  is the minimal solution of (4.8).

Furthermore,  $v_{\beta,min}$  is the limit of the increasing sequence the bounded solutions  $\{v_n\}$  of (3.11), therefore  $w_{\beta,min}$  is the limit of the increasing sequence  $\{w_{\beta,n}\} := \{v_n + \beta \ln \lambda\}$  of the solutions of

$$\begin{cases} -\Delta w_{\beta,n} + \frac{V}{(e^{\nu_1-\nu_2} + e^{w_{\beta,n-1}})^a} \frac{e^{w_{\beta,n}}}{e^{\nu_1-\nu_2} + e^{w_{\beta,n}}} = f_1 - f_2 & \text{in } \mathbb{R}^2, \\ w_{\beta,n} = \beta \ln \lambda + O(1) & \text{as } |x| \rightarrow \infty. \end{cases} \quad (4.9)$$

By the comparison principle, the mapping  $\beta \in (-2(N-M), \beta^*) \mapsto w_{\beta,n}$  is increasing for any  $n$ , and this is also true for  $\beta \mapsto w_{\beta,min}$ . By (3.15) there holds for any  $n \in \mathbb{N}$ ,

$$w_0(x) \leq w_{\beta,n}(x) \leq w_{\beta,min}(x) \leq c_{20} + \frac{R^2 \|g_\beta\|_{L^\infty}}{2} (\ln R + 1) + \beta \ln \lambda(x) \quad \text{in } \mathbb{R}^2. \quad (4.10)$$

*Uniformly upper bound for  $\{w_{\beta,min}\}_\beta$ .* Let  $\bar{v}_2 = \Gamma * g_{\beta^*}$ , then  $\bar{v}_2 = \Gamma * (f_1 - f_2) + \beta^* \ln \lambda - 2 \ln \Lambda$  and

$$\lim_{|x| \rightarrow \infty} \frac{\bar{v}_2(x)}{\ln |x|} = 2(N-M) + \beta^* > 0.$$

Since  $\bar{v}_2$  is a super solution of (4.9), we have by comparison

$$w_{\beta,n} \leq \bar{v}_2 \quad \text{in } \mathbb{R}^2,$$

which implies that for any  $\beta \in (-2(N-M), \beta^*)$

$$w_{\beta,min} \leq \bar{v}_2 \quad \text{in } \mathbb{R}^2.$$

Hence there exists  $w_{\beta^*,min} = \lim_{\beta \uparrow \beta^*} w_{\beta,min}$  and

$$w_{\beta^*,min} \leq \bar{v}_2 \quad \text{in } \mathbb{R}^2,$$

and therefore

$$w_{\beta^*,min}(x) \leq \beta^* \ln |x| - 2 \ln \ln |x| + c, \quad (4.11)$$

for some  $c \in \mathbb{R}$ .



*Lower bound for  $w_{\beta^*, \min}$ .* From Proposition 4.1, the equation

$$-\Delta w + \frac{V}{e^{a(\nu_1 - \nu_2)}} \frac{e^w}{e^{\nu_1 - \nu_2} + e^w} = f_1 - f_2 \quad \text{in } \mathbb{R}^2 \quad (4.12)$$

has a unique solution  $w_{\beta^*}$ , with the following asymptotic behavior

$$w_{\beta^*}(x) = \beta^* \ln |x| - 2 \ln \ln |x| + O(1) \quad \text{as } |x| \rightarrow +\infty,$$

and  $w_{\beta^*}$  is the limit of the solutions  $w_\beta$  of (4.4) for  $\beta \in (-2(N - M), \beta^*)$  satisfying

$$w_\beta(x) = \beta \ln |x| + O(1) \quad \text{as } |x| \rightarrow +\infty.$$

Since  $w_\beta$  is a subsolution for (4.8) it is upper bounded  $w_{\beta, \min}$  by the same comparison method as the ones used previously. Therefore  $w_{\beta^*} \leq w_{\beta^*, \min}$ . Combining (4.11) with the expression of  $w_{\beta^*}$  given in (4.11), we infer that

$$w_{\beta^*, m}(x) = \beta^* \ln |x| - 2 \ln \ln |x| + O(1) \quad \text{as } |x| \rightarrow +\infty.$$

Clearly the flux identity holds as in the previous theorem, which ends the proof.  $\square$

## 5 Multiple solutions

### 5.1 Non-topological solutions

Let  $\beta \neq 0$  and  $u_\beta$  be a solution of problem (1.1) with the asymptotic behavior

$$u_\beta(x) = \beta \ln |x| + O(1) \quad \text{as } |x| \rightarrow +\infty.$$

Then  $u_\beta$  can be written under the form

$$u_\beta = -\nu_1 + \nu_2 + \beta \ln \lambda + v_\beta,$$

where  $v_\beta$  is a bounded solution of the following equation equivalent to (3.1)

$$-\Delta v + W_\beta \frac{e^v}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^v)^{1+a}} = g_\beta \quad \text{in } \mathbb{R}^2 \quad (5.1)$$

with  $W_\beta = V \lambda^{-a\beta}$  and

$$g_\beta = f_1 - f_2 + \beta \Delta \ln \lambda,$$

which is a smooth function with compact support in  $B_{r_0}(0)$  and verifies

$$\int_{\mathbb{R}^2} g_\beta dx = 2\pi[2(N - M) + \beta].$$

As for  $W_\beta$  it satisfies

$$\lim_{x \rightarrow p_j} W_\beta(x) = A_0 \left( \prod_{i \neq j} |p_j - p_i|^{2n_i} \right)^{-a}, \quad \lim_{x \rightarrow q_j} W_\beta(x) = 0 \quad \text{and} \quad \lim_{|x| \rightarrow \infty} W_\beta(x) |x|^{2aN + a\beta} = A_0.$$

The existence of multiple solutions states as follows:

**Proposition 5.1** *Let  $N, M$  be positive integers and  $\beta^\sharp$  be given in (1.10). Then for any  $\beta > \beta^\sharp$  problem (5.1) possesses a sequence of solutions  $v_{\beta,i}$  such that*

$$\int_{\mathbb{R}^2} W_\beta \frac{e^{v_{\beta,i}}}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_{\beta,i}})^{1+a}} dx = 2\pi[2(N-M) + \beta] \quad (5.2)$$

and

$$v_{\beta,i}(x) = c_{\beta,i} + O(|x|^{-\frac{a\beta+2aN-2}{a\beta+2aN-1}}) \quad \text{as } |x| \rightarrow +\infty$$

with

$$c_{\beta,i} \rightarrow \infty \quad \text{as } i \rightarrow +\infty.$$

**Proof.** By Theorem 2.1, for any  $A > 0$  the equation

$$-\Delta w + e^{-A(1+a)} W_\beta e^w = g_\beta \quad \text{in } \mathbb{R}^2 \quad (5.3)$$

has a unique bounded solution  $w_A$ . We note that

$$w_A = w_0 + A(1+a),$$

where  $w_0$  is the bounded solution of (5.3) with  $A = 0$ . Note that for any  $A \geq A^* = a^{-1}\|w_0\|_{L^\infty(\mathbb{R}^2)}$ ,

$$w_A \geq A \quad \text{in } \mathbb{R}^2.$$

*Step 1: construction of an approximating sequence.* We set  $v_0 := w_A$  and define  $H_t(\cdot)$  by

$$H_0(t, \cdot) = \begin{cases} A_0 & \text{in } \Sigma_1, \\ 0 & \text{in } \Sigma_2, \\ W_\beta \frac{e^t}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_0})^{1+a}} & \text{in } \mathbb{R}^2 \setminus \Sigma. \end{cases}$$

Under the assumptions,  $H_0(t, \cdot) \in L^\delta(\mathbb{R}^2)$  for some  $\delta > 1$  and there exists a unique (and explicit) real number  $t_1$  such that

$$\int_{\mathbb{R}^2} H_0(t_1, x) dx = 2\pi(2(N-M) + \beta).$$

We construct first a bounded solution  $v_1$  of

$$-\Delta v + W_\beta \frac{e^v}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_0})^{1+a}} = g_\beta \quad \text{in } \mathbb{R}^2. \quad (5.4)$$

We set

$$w_1 = \Phi * (g_\beta - H_0(t_1, \cdot)).$$

By Lemma 2.2,  $w_1$  is bounded. Put  $\bar{v} = \|v_0\|_{L^\infty} + w_1 + \|w_1\|_{L^\infty} + |t_1|$ . Then

$$\frac{e^{\bar{v}}}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_0})^{1+a}} \geq \frac{e^{t_1}}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_0})^{1+a}},$$

therefore

$$-\Delta \bar{v} + W_\beta \frac{e^{\bar{v}}}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_0})^{1+a}} - g_\beta \geq g_\beta - H(t_1, \cdot) + W_\beta \frac{e^{t_1}}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_0})^{1+a}} - g_\beta \geq 0.$$

Hence  $\bar{v}$  is a supersolution of (5.4). Since

$$-\Delta v_0 + W_\beta \frac{e^{v_0}}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_0})^{1+a}} - g_\beta \leq W_\beta e^{v_0} \left( \frac{1}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_0})^{1+a}} - \frac{1}{e^{(1+a)A}} \right) \leq 0,$$

$v_0$  is a subsolution of (5.4) dominated by  $\bar{v}$ . Hence there exists a solution  $v = v_1$  of (5.4) satisfying

$$v_0 \leq v_1 \leq \bar{v}.$$

Since  $a\beta + 2aN > 2$ , we have from Lemma 2.2

$$v_1(x) = c_{1,\beta} + O(|x|^{-\frac{a\beta+2aN-2}{a\beta+2aN-1}}) \quad \text{as } |x| \rightarrow \infty.$$

We define a sequence  $\{v_n\}_{n \in \mathbb{N}}$  with  $v_0 = w_A$  and  $v = v_n$  is the bounded solution of

$$-\Delta v + W_\beta \frac{e^v}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_{n-1}})^{1+a}} = g_\beta \quad \text{in } \mathbb{R}^2. \quad (5.5)$$

Assume that we have proved the existence and boundedness of the functions  $v_k$  for  $k < n$  and that there holds  $v_0 \leq v_1 \leq \dots \leq v_{n-1}$ . We define  $H_{n-1}(t, \cdot)$  by

$$H_{n-1}(t, \cdot) = \begin{cases} A_0 & \text{in } \Sigma_1 \\ 0 & \text{in } \Sigma_2 \\ W_\beta \frac{e^t}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_{n-1}})^{1+a}} & \text{in } \mathbb{R}^2 \setminus \Sigma \end{cases}$$

and  $t_n$  is the unique real number such that

$$\int_{\mathbb{R}^2} H_{n-1}(t, x) dx = 2\pi(2(N - M) + \beta).$$

Since  $v_0 \leq v_1 \leq \dots \leq v_{n-1}$ , there holds  $t_0 < t_1 < \dots < t_n$ . If we set  $w_n = \Gamma * (g_\beta - H_{n-1}(t_n, \cdot))$ , clearly  $\bar{v}_n := \|v_{n-1}\|_{L^\infty} + w_n + \|w_n\|_{L^\infty} + |t_n|$  is a supersolution. Furthermore

$$\begin{aligned} & -\Delta v_{n-1} + W_\beta \frac{e^{v_{n-1}}}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_{n-1}})^{1+a}} - g_\beta \\ & \leq W_\beta e^{v_{n-1}} \left( \frac{1}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_{n-1}})^{1+a}} - \frac{1}{(e^{\nu_1 - \nu_2} \lambda^{-\beta} + e^{v_{n-2}})^{1+a}} \right) \leq 0. \end{aligned}$$

Hence  $v_{n-1}$  is a subsolution. A solution  $v = v_n$  of (5.5) satisfying  $v_{n-1} \leq v_n \leq \bar{v}_n$  exists. It is bounded and satisfies

$$v_n(x) = c_{n,\beta} + O(|x|^{-\frac{a\beta+2aN-2}{a\beta+2aN-1}}) \quad \text{as } |x| \rightarrow \infty \quad (5.6)$$

for some  $c_{n,\beta}$ , and the sequence  $\{c_{n,\beta}\}$  is nondecreasing, and by Corollary 2.1

$$|\nabla v_n(x)| = O(|x|^{-1-\frac{a\beta+2aN-2}{a\beta+2aN-1}}) \quad \text{as } |x| \rightarrow \infty. \quad (5.7)$$

*Uniformly upper bound for  $\{v_n\}_n$ .* Let  $\bar{v}_\beta = \Gamma * g_\beta$ , then it is a supersolution of (5.5) for any  $n \in \mathbb{N}$  and satisfies

$$\lim_{|x| \rightarrow \infty} \frac{\bar{v}_\beta(x)}{\ln|x|} = 2(N-M) + \beta.$$

This implies that for any  $\epsilon > 0$ , there exists  $C_\epsilon > 0$  such that

$$\bar{v}_\beta(x) \leq (2(N-M) + \beta + \epsilon) \ln(|x| + 1) + C_\epsilon \quad \text{in } \mathbb{R}^2. \quad (5.8)$$

Note that  $\bar{v}_\beta$  is a super solution of (5.5) and by the comparison principle

$$v_n \leq \bar{v}_\beta \quad \text{in } \mathbb{R}^2.$$

Therefore the limit of the sequence of  $\{v_n\}$  as  $n \rightarrow \infty$  exists. As it depends also on  $A$ , we denote it by  $v_{\beta,A}$  and there holds

$$v_{\beta,A} \leq \bar{v}_\beta \quad \text{in } \mathbb{R}^2.$$

Furthermore  $v_{\beta,A}$  is a locally bounded solution of (5.1) which satisfies

$$A \leq v_{\beta,A}(x) \leq (2(N-M) + \beta + \epsilon) \ln(|x| + 1) + C_\epsilon \quad \text{in } \mathbb{R}^2. \quad (5.9)$$

Because of the above lower estimate, the functions  $x \mapsto \frac{e^{v_n(x)}}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_n(x)})^{1+a}}$  are upper bounded on  $\mathbb{R}^2$  by some constant depending on  $A$  and  $\beta$  but independent of  $n$ , and this estimate holds true if  $v_n$  is replaced by  $v_{\beta,A}$ . Hence for any  $R > 0$ ,

$$-\int_{|x|=R} \frac{\partial v_n}{\partial r} dS + \int_{B_R} W_\beta \frac{e^{v_n}}{e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_n}} dx = \int_{B_R} g_\beta dx.$$

By (5.7) the integral term on  $|x| = R$  tends to 0 when  $R \rightarrow \infty$ , therefore

$$\int_{\mathbb{R}^2} W_\beta \frac{e^{v_n}}{e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_n}} dx = \int_{\mathbb{R}^2} g_\beta dx = 2\pi(2(N-M) + \beta). \quad (5.10)$$

Since  $\frac{e^{v_n}}{e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_n}}$  is bounded independently of  $n$ , it follows by the dominated convergence theorem that

$$\int_{\mathbb{R}^2} W_\beta \frac{e^{v_{\beta,A}}}{e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_{\beta,A}}} dx = \int_{\mathbb{R}^2} g_\beta dx. \quad (5.11)$$

Combining this identity with the estimate

$$\left| g_\beta(x) - W_\beta(x) \frac{e^{v_{\beta,A}(x)}}{(e^{\nu_1-\nu_2}\lambda^{-\beta} + e^{v_{\beta,A}(x)})^{1+a}} \right| \leq c_{21}(1+|x|)^{-2aN-a\beta},$$

and using Lemma 2.2, we infer that  $v_{\beta,A}$  is uniformly bounded in  $\mathbb{R}^2$  and that there exists  $c_{\beta,A} > A$  such that

$$v_{\beta,A}(x) = c_{\beta,A} + O(|x|^{-\frac{a\beta+2aN-2}{a\beta+2aN-1}}) \quad \text{as } |x| \rightarrow +\infty. \quad (5.12)$$

In order to construct the sequence of solutions, we start with  $A = A_0 = 1$ , then take  $A = A_1 = \inf\{k \in \mathbb{N} : k > c_{\beta,A}\}$  and we iterate, defining by induction  $A_{i+1} = \inf\{k \in \mathbb{N} : k > c_{\beta,A_i}\}$ .  $\square$

**Proof of Theorem 1.2 part (ii) and Theorem 1.4. Multiple solutions.** Let

$$u_{\beta,i} = -\nu_1 + \nu_2 + \beta \ln \lambda + v_{\beta,i},$$

where  $\{v_{\beta,i}\}_i$  are a sequence solutions of (5.1) by Proposition 5.1. Then  $\{u_{\beta,i}\}_i$  is a sequence of non-topological solutions in type II of (1.1) verifying (1.13) and with total magnetic flux  $2\pi[2(N - M) + \beta]$ . The proof is now complete.  $\square$

## 5.2 Topological solution

**Proof of Theorem 1.5. Multiple Topological solutions.** Let  $u$  be a topological solution for problem (1.1). We can write it as  $u = -\nu_1 + \nu_2 + v$  where  $v$  is a bounded regular solution of

$$-\Delta v + V \frac{e^v}{(e^{\nu_1 - \nu_2} + e^v)^{1+a}} = g_0 \quad \text{in } \mathbb{R}^2 \quad (5.13)$$

with

$$g_0 = f_1 - f_2,$$

where the functions  $f_1$  and  $f_2$  have been defined in (2.4). They are smooth, have compact support in  $B_{r_0}(0)$  and the flux identity (2.5) is satisfied.

*Claim:* Problem (5.13) possesses a sequence of bounded solutions  $\{v_i\}_i$  such that

$$\int_{\mathbb{R}^2} V \frac{e^{v_i}}{(e^{\nu_1 - \nu_2} + e^{v_i})^{1+a}} dx = 4\pi(N - M) \quad (5.14)$$

and

$$v_i(x) = c_i + O(|x|^{-\frac{2aN-2}{2aN-1}}) \quad \text{as } |x| \rightarrow +\infty \quad (5.15)$$

with  $c_i \rightarrow +\infty$  as  $i \rightarrow +\infty$ .

This can be proved as follows: given  $A > 0$ , let  $w_A$  be the bounded solution of

$$-\Delta w + e^{-A(1+a)} V e^w = g_0 \quad \text{in } \mathbb{R}^2. \quad (5.16)$$

We note that

$$w_A = w_0 + A(1 + a),$$

where  $w_0$  is a bounded solution of (5.3) with  $A = 0$ . Note that for any  $A \geq A^* = a^{-1} \|w_0\|_{L^\infty(\mathbb{R}^2)}$ ,

$$w_A \geq A \quad \text{in } \mathbb{R}^2.$$

We set  $\mu_0 = w_A$ , and define  $\mu_n$  ( $n \in \mathbb{N}$ ) to be the solution of

$$-\Delta \mu_n + V \frac{e^{\mu_n}}{(e^{\nu_1 - \nu_2} + e^{\mu_{n-1}})^{1+a}} = g_0 \quad \text{in } \mathbb{R}^2. \quad (5.17)$$

As in the proof of Proposition 5.1, the mapping  $n \mapsto \mu_n$  is increasing and  $\mu_n$  is uniformly upper bounded. It converges to  $v_A$  as  $n \rightarrow +\infty$ , and  $v_A$  is a weak solution of (5.13). Since  $V(x) \leq c_{22}|x|^{-2aN}$  when  $|x| \rightarrow +\infty$ , and  $2aN > 2$ , there holds

$$\mu_n(x) = c_{n,A} + O\left(|x|^{-\frac{2aN-2}{2aN-1}}\right) \quad \text{and} \quad |\nabla \mu_n(x)| \leq c_{22}|x|^{-1-\frac{2aN-2}{2aN-1}} \quad \text{as } |x| \rightarrow +\infty.$$

Integrating (5.17) on  $B_R$  and letting  $R \rightarrow \infty$  yields

$$\int_{\mathbb{R}^2} V \frac{e^{\mu_n}}{(e^{\nu_1-\nu_2} + e^{\mu_{n-1}})^{1+a}} dx = \int_{\mathbb{R}^2} (f_1 - f_2) dx = 4\pi(N - M).$$

Because  $\frac{e^{\mu_n}}{(e^{\nu_1-\nu_2} + e^{\mu_{n-1}})^{1+a}}$  is uniformly bounded and  $V \in L^1(\mathbb{R}^2)$  we obtain by the dominated convergence theorem

$$\int_{\mathbb{R}^2} V \frac{e^{v_A}}{(e^{\nu_1-\nu_2} + e^{v_A})^{1+a}} dx = 4\pi(N - M). \quad (5.18)$$

Therefore,

$$v_A(x) = c_A + O(|x|^{-\frac{2aN-2}{2aN-1}}) \quad \text{as } |x| \rightarrow +\infty, \quad (5.19)$$

and the end of the proof is similar as the one of Proposition 5.1.  $\square$

## 6 Nonexistence

**Lemma 6.1** *Let  $aN < 1$ . Then*

(i) *problem (1.1) has no solution  $u_\beta$  verifying*

$$u_\beta(x) - \beta \ln |x| = o(\ln |x|) \quad \text{as } |x| \rightarrow +\infty \quad (6.1)$$

*for  $\beta^* < \beta \leq 0$ .*

(ii) *problem (1.1) has no solution  $u_\beta$  verifying (6.1) if  $0 \leq \beta < \frac{2-aN}{a}$ ;*

(iii) *problem (1.1) has no topological solution.*

**Proof.** We recall that a solution verifying (6.1) with  $\beta < 0$  (resp.  $\beta > 0$ ) is called non-topological of type II (resp. type I). Given a function, we denote by  $\bar{w}$  the circular average of  $w$ , i.e.

$$\bar{w}(r) = \frac{1}{2\pi r} \int_{\partial B_r(0)} w(\xi) d\theta(\xi) = \frac{1}{2\pi} \int_0^{2\pi} w(r, \theta) d\theta.$$

For  $|x| \geq r_0$ , there exists  $c_{23} > 0$  such that

$$\mathbf{P}(x) \geq c_{23}|x|^{-aN}$$

and we set, for all  $x \in \mathbb{R}^2$

$$h_u(x) = \mathbf{P}(x) \frac{e^{u(x)}}{(1 + e^{u(x)})^{1+a}}. \quad (6.2)$$

**Proof of (i).** If  $u$  is a non-topological solution of Type I, it satisfies  $u(x) \leq c_{24}$  for  $|x| \geq r_0$  and  $c_{24} > 0$ . By Jensen inequality

$$\bar{h}_u(r) \geq \frac{c_{25}A_0r^{-aN}}{(1 + e^{c_{24}})^{1+a}} \overline{e^{u(x)}} \geq c_{26}e^{\bar{u}(r)} \quad \text{for } r > r_0, \quad (6.3)$$

and from (6.1), there exist  $\epsilon_0 \in (0, 1)$  and  $c_{27} > 0$  such that for  $r > r_0$ ,

$$\bar{h}_u(r) \geq \frac{c_{27}}{r^{2-\epsilon_0}}. \quad (6.4)$$

Then (1.1) implies that

$$(r\bar{u}_r)_r \geq \frac{c_{27}}{r^{1-\epsilon_0}} \quad \text{for } r \geq r_0,$$

thus, integrating the above inequalities, we obtain

$$r\bar{u}_r(r) - r_0\bar{u}_r(r_0) \geq c_{28}(r^{\epsilon_1} - r_0^{\epsilon_1}),$$

where  $\bar{u}_r = \frac{d\bar{u}}{dr}$  and  $c_{27}, c_{28} > 0$ . Hence there holds

$$\bar{u}(r) \geq \bar{u}(r_0) + (r_0\bar{u}_r(r_0) - c_{28}r_0^{\epsilon_1}) \ln r + \frac{c_{28}}{\epsilon_1}r^{\epsilon_1} \quad \text{for } r > r_0.$$

As a consequence,

$$\bar{u}(r) \rightarrow +\infty \quad \text{as } r \rightarrow +\infty, \quad (6.5)$$

which contradicts the fact that  $u$  is bounded from above.

**Proof of (ii).** If  $u$  is a non-topological solution of Type II and  $0 \leq \beta < \frac{2-aN}{a}$ , then

$$h_u(x) \geq \mathbf{P}(x) \frac{1}{(1 + e^u)^a} \geq \frac{c_{29}}{|x|^{2-\epsilon_1}}$$

for some  $\epsilon_1 > 0$  and  $c_{29} > 0$ . Then (1.1) implies that

$$(r\bar{w}_r)_r \geq \frac{c_{30}}{r^{1-\epsilon_1}} \quad \text{for } r \geq r_0.$$

Hence there holds

$$\bar{w}(r) \geq \bar{w}(r_0) + (r_0\bar{w}_r(r_0) - c_{30}r_0^{\epsilon_1}) \ln r + \frac{c_{30}}{\epsilon_1}r^{\epsilon_1} \quad \text{for } r > r_0,$$

which contradicts (6.1).

**Proof of (iii).** The proof is the same as above.  $\square$

**Proof of Theorem 1.6.** If  $aN < 1$ , Lemma 6.1 implies that then problem (1.1) has no solutions  $u_\beta$  for  $\beta^* < \beta < \frac{2-aN}{a}$  verifying  $u_\beta(x) = \beta \ln |x| + O(1)$ .

Next we assume that  $aN = 1$ , and  $u$  is a topological solution (1.1). Hence  $u$  is bounded at infinity and

$$h_u(x) \geq \mathbf{P}(x) \frac{e^u}{(1 + e^u)^a} \geq \frac{c_{31}}{|x|^{-2}}.$$

Then (1.1) implies that

$$(r\bar{u}_r)_r \geq \frac{c_{32}}{r} \quad \text{for } r \geq r_0.$$

By integrating this inequality we encounter a contradiction with the fact that  $u$  is bounded at infinity.  $\square$

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