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COMPETITION IN PERIODIC MEDIA: III – EXISTENCE & STABILITY OF SEGREGATED PERIODIC COEXISTENCE STATES

LÉO GIRARDIN¹ AND ALESSANDRO ZILIO²

ABSTRACT. In this paper we consider a system of parabolic reaction-diffusion equations with strong competition and two related scalar reaction-diffusion equations. We are mainly concerned with the case of periodic coefficients and periodic solutions. We show that, for sufficiently large periods, these models have stationary, non-constant, fully non-trivial and stable solutions. We compare our results with already known results about the existence and non-existence of such solutions. Finally, we provide ecological interpretations for these results in terms of resistance against an invasion.

1. INTRODUCTION

We construct stable periodic sign-changing steady states in one-dimensional spatially periodic media for the equation

$$(1.1) \quad \partial_t z - \partial_{xx} z = f(z, x)$$

and its quasi-linear counterpart

$$(1.2) \quad \partial_t (\sigma(z)z) - \partial_{xx} z = f(z, x),$$

where

$$f : (z, x) \mapsto \mu_1(x) \left(a_1 - \frac{1}{\alpha} z \right) z^+ - \frac{1}{d} \mu_2(x) \left(a_2 + \frac{1}{d} z \right) z^-$$

and the positive function σ is

$$\sigma : z \mapsto \mathbf{1}_{z>0} + \frac{1}{d} \mathbf{1}_{z<0}.$$

Here L , a_1 , a_2 , α and d are positive constants, $\mu_1, \mu_2 \in L^\infty(\mathbb{R}, (0, +\infty))$ are positive L -periodic functions, $z^+ = \max(z, 0)$ and $z^- = -\min(z, 0)$ (so that $z = z^+ - z^-$).

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We also construct stable periodic coexistence steady states for the following competition–diffusion system:

$$(1.3) \quad \begin{cases} \partial_t u_1 - \partial_{xx} u_1 = \mu_1(x) (a_1 - u_1) u_1 - k\omega(x) u_1 u_2 \\ \partial_t u_2 - d\partial_{xx} u_2 = \mu_2(x) (a_2 - u_2) u_2 - \alpha k\omega(x) u_1 u_2 \end{cases}$$

where $\omega \in L^\infty(\mathbb{R}, (0, +\infty))$ is positive and L -periodic (with a normalized mean value, say).

System (1.3) belongs to the wider class of elliptic or parabolic systems of Lotka–Volterra type in the presence of strong competition, and (1.1) and (1.2) are related to its singular *strong competition limit* $k \rightarrow +\infty$. To our knowledge, the study of the strong competition limit appeared first in [9] as a way to model biological species that are fiercely competing for the same resource. The literature on this subject is very vast, varying from existence and uniqueness results [8], multiplicity results in presence of strong competition [9] and the rigorous proof of Gause’s competitive exclusion [20, 11] stating that in the homogeneous case, non-constant solutions are necessarily unstable (in convex domains). We refer the interested reader to these contributions and the references therein.

More recently, the strong competition limit in periodic media was the object of investigation of two papers [18, 19] by the first author and Nadin. According to [19], (1.2) is the equation satisfied, in the strong competition limit, by the quantity $\alpha u_1 - d u_2$ with (u_1, u_2) solution of (1.3). Notice that, by normalizing (u_1, u_2) , we can assume without loss of generality $a_1 = a_2 = 1$. This is assumed indeed from now on. Notice also that, although all results of [18, 19] are stated for $\omega = 1$, they are readily extended to the case of non-constant ω .

Steady states of (1.1) and of (1.2) satisfy the same elliptic semilinear equation:

$$(1.4) \quad -z''(x) = \mu_1(x) \left(1 - \frac{1}{\alpha} z(x)\right) z^+(x) - \frac{1}{d} \mu_2(x) \left(1 + \frac{1}{d} z(x)\right) z^-(x).$$

However, due to the different time dependencies, (1.1) and (1.2) involve in general different notions of stability and therefore different eigenproblems. Before going any further, let us precise this important point.

1.1. Notions of stability. For any functional space X , we let $X_{L\text{-per}}$ denote the set of L -periodic functions that, once restricted to any interval of length L are elements of X . Accordingly, for any second order monotone elliptic operator \mathcal{L} , $\lambda_{1,L\text{-per}}(-\mathcal{L})$ denotes the periodic principal eigenvalue of \mathcal{L} given by the Krein–Rutman theorem. Recall that if (u_1, u_2) is a solution of (1.3), then the system satisfied by $(u_1, 1 - u_2)$ is a monotone system, whence its linearization admits indeed a periodic principal eigenvalue (details can be found in [18]).

Hereafter, a solution $z \in H_{L\text{-per}}^2(\mathbb{R})$ of (1.4) such that the L -periodic function

$$f_1[z] : x \mapsto \partial_1 f(z(x), x),$$

is well-defined (at least weakly) is referred to as *linearly stable in the sense of (1.1)* if

$$\lambda_{1,L\text{-per}} \left(-\frac{d^2}{dx^2} - f_1[z] \right) > 0$$

and as *linearly stable in the sense of (1.2)* if

$$\lambda_{1,L\text{-per}} \left(-\hat{\sigma}(z) \frac{d^2}{dx^2} - \hat{\sigma}(z) f_1[z] \right) > 0,$$

with

$$\hat{\sigma} : z \mapsto \mathbf{1}_{z \geq 0} + d\mathbf{1}_{z < 0}.$$

The constant solutions of (1.4) are α , $-d$ and 0. It is easily verified that α and $-d$ are linearly stable in both senses whereas 0 is linearly unstable (namely, not linearly stable) in both senses.

The definition of linear stability in the sense of (1.2) can be formally understood by plugging perturbations of the form $e^{-\lambda t}\varphi(x)$, with φ L -periodic, into the equation (1.2) linearized at an almost everywhere nonzero steady state z . Indeed, such a perturbation solves the linear equation if and only if

$$-\lambda\sigma(z)\varphi - \varphi'' = f_1[z]\varphi,$$

that is, due to the almost everywhere equality $\sigma(z(x))\hat{\sigma}(z(x)) = 1$, if and only if

$$-\hat{\sigma}(z)\varphi'' - \hat{\sigma}(z)f_1[z]\varphi = \lambda\varphi.$$

Similarly, a steady state solution (u_1, u_2) of (1.3) is a solution of

$$(1.5) \quad \begin{cases} -u_1''(x) = \mu_1(x)(1 - u_1(x))u_1(x) - k\omega(x)u_1(x)u_2(x) \\ -du_2''(x) = \mu_2(x)(1 - u_2(x))u_2(x) - \alpha k\omega(x)u_1(x)u_2(x) \end{cases}$$

and is referred to as *linearly stable* if

$$\lambda_{1,L\text{-per}} \left(- \begin{pmatrix} \frac{d^2}{dx^2} + \mu_1(1 - 2u_1) - k\omega u_2 & k\omega u_1 \\ \alpha k\omega u_2 & d\frac{d^2}{dx^2} + \mu_2(1 - 2u_2) - \alpha k\omega u_1 \end{pmatrix} \right) > 0.$$

The steady states $(1, 0)$ and $(0, 1)$ are linearly stable whereas $(0, 0)$ is linearly unstable.

By analogy with the spatially homogeneous setting and in view of the stability of the constant solutions, (1.1), (1.2) and (1.3) are sometimes referred to as *bistable*. However our main contribution is to prove that this terminology can be misleading: because of the spatial heterogeneity, a third stable state can very well exist.

Let us point out that the previous two parts of the series “*Competition in periodic media*”[18, 19] only used the notion of stability in the sense of the system (1.3). This explains why the two notions of stability for the segregated equation (1.4) are only introduced now.

1.2. Main results. Let $(r_0, r_1, r_2) \in (0, 1)^3$ such that $2r_0 + 2r_1 + 2r_2 = 1$. Let $(M_1, M_2) \in (0, +\infty)^2$ and define two 1-periodic functions μ_1^* and μ_2^* by

$$\begin{aligned} (\mu_1^*)|_{[0,1]} &= M_1\mathbf{1}_{[0,r_1]} + M_1\mathbf{1}_{[r_1+2r_0+2r_2,1]} \\ (\mu_2^*)|_{[0,1]} &= M_2\mathbf{1}_{[r_1+r_0, r_1+r_0+2r_2]} \end{aligned}$$

and, for all $L > 0$,

$$(\mu_1^L, \mu_2^L) : x \mapsto (\mu_1^*, \mu_2^*) \left(\frac{x}{L} \right).$$

Our first main result is concerned with the equation (1.4).

Theorem 1.1. *There exists $\underline{L} > 0$ such that, for all $L > \underline{L}$, (1.4) with $(\mu_1, \mu_2) = (\mu_1^L, \mu_2^L)$ or with $(\mu_1, \mu_2) = (\mu_1^L + \mu_2^L, \mu_1^L + \mu_2^L)$ admits a linearly stable in both senses, sign-changing, L -periodic solution.*

Furthermore, for all $L > \underline{L}$, there exist a neighborhood U_L of (μ_1^L, μ_2^L) in the topology of $(L_{L\text{-per}}^\infty)^2$ and a neighborhood V_L of $\mu_1^L + \mu_2^L$ in the topology of $(L_{L\text{-per}}^\infty)$ such that, for all $(\mu_1, \mu_2) \in U_L$ and all $\mu \in V_L$, (1.4) with (μ_1, μ_2) or (μ, μ) admits a linearly stable in both senses, sign-changing, L -periodic solution.

This first result will be proved by explicit construction of v and non-trivial application of the implicit function theorem.

In biological terms, the growth rate $\mu_1^L + \mu_2^L$ corresponds to a periodic environment where large favorable areas are separated by large neutral areas. A neutral area could be, say, in a woodland inhabited by herbivorous animals looking for glades, an area densely covered by trees where predators live and hide and where linear death rates roughly equal linear birth rates and no intraspecific competition occurs. The associated stable steady state describes the situation where one competitor settles in the evenly numbered favorable areas whereas the other settles in the oddly numbered ones. This particular form is illustrated by Figure 2.2.1.

Let us point out that well-known density results yield immediately the following corollary.

Corollary 1.2. *For all $L > \underline{L}$, there exists $(\mu_1, \mu_2) \in (\mathcal{C}_{L\text{-per}}^\infty(\mathbb{R}, (0, +\infty)))^2$ such that (1.4) admits a linearly stable in both senses, sign-changing, L -periodic solution.*

Our second main result is concerned with the system (1.5) and states that the existence of stable steady states for the segregated equation implies the existence of stable steady states for the strongly competitive system. It will be proved as a consequence of Theorem 1.1 and of degree theory.

Theorem 1.3. *For all $L > \underline{L}$, there exist $k^* > 0$ and $(\mu_1, \mu_2) \in (\mathcal{C}_{L\text{-per}}^\infty(\mathbb{R}, (0, +\infty)))^2$ such that, for all $k > k^*$, (1.5) admits a linearly stable, component-wise positive, L -periodic solution.*

1.3. Discussion and comparison with known results. Theorem 1.1 and Theorem 1.3 complement interestingly a result of the first author [18, Theorem 1.2] stating that, provided L is sufficiently small, that is

$$L \in \left(0, \pi \left(\left(\max_{[0, L]} \mu_1 \right)^{-\frac{1}{2}} + \sqrt{d} \left(\max_{[0, L]} \mu_2 \right)^{-\frac{1}{2}} \right) \right),$$

and provided k is large enough, all L -periodic coexistence states are unstable and vanish as $k \rightarrow +\infty$.

Theorem 1.1 is also strictly related to a result due to Ding, Hamel and Zhao [12, Theorem 1.5] which shows in particular that the regular bistable equation

$$\partial_t z - \partial_{xx} z = g_L(x, z),$$

with $g_L : (z, x) \mapsto g(z, \frac{x}{L})$, g 1-periodic with respect to x and independent of L , 0 and 1 linearly stable steady states (in the standard sense) and $\theta \in \mathcal{C}_{1\text{-per}}(\mathbb{R}, (0, 1))$ intermediate zero of g , admits bistable pulsating fronts connecting 0 and 1 provided L is large enough and the nonlinearity g satisfies

$$\min_{x \in [0, L]} \int_0^1 g(x, z) dz > 0 \text{ and } \min_{x \in [0, L]} \frac{\partial g}{\partial z}(x, \theta(x)) > 0.$$

Their proof is based on a very important result by Fang and Zhao [16] stating in a general setting that bistable pulsating fronts exist if all intermediate periodic steady states are unstable and invadable. Therefore the proof of Ding–Hamel–Zhao basically shows that the above conditions imply the nonexistence of stable periodic steady states. Importantly,

- on one hand, the family of scaled functions $(f_L)_{L>\underline{L}}$ in Theorem 1.1 satisfies

$$\min_{x \in [0, L]} \int_{-d}^{\alpha} f_L(x, z) dz = 0 \quad \text{for all } L > \underline{L}$$

(recalling that here the two constant stable states are $-d$ and α instead of 0 and 1);

- on the other hand, any family of regularized and positive functions obtained from Corollary 1.2 satisfies indeed the above two positivity conditions, but by the result of Ding–Hamel–Zhao cannot be of the prescribed scaled form as L varies (in other words, the neighborhoods U_L and V_L obtained with the implicit function theorem are not uniform with respect to L and shrink as $L \rightarrow +\infty$).

We point out that a recent paper by Zlatős [23] constructed an example of periodic bistable nonlinearity admitting no pulsating front. His result is very related to ours but remains qualitatively different: we focus on stable intermediate steady states whereas Zlatős focuses on nonexistence of transition fronts. Furthermore, our construction has a very simple ecological interpretation and is valid for all large periods, whereas the construction of Zlatős requires a very precise period. In this regard, our paper is an interesting complement.

Theorem 1.1 is also related to a family of results stating, loosely speaking, that the geometry of a homogeneous domain with boundary can block bistable propagation. See for instance Berestycki–Bouhours–Chapuisat [3] and references therein.

Ecologically speaking, Theorem 1.3 shows that *strong interspecific competition* and *heterogeneity of the habitat* can lead together to *spatial segregation* and therefore to *speciation* and *increased biodiversity*. Having this interpretation in mind, we notice that the strength of the competition is crucial: indeed, in the weak competition case, Dockery–Hutson–Mischaikow–Pernarowski [13] showed on the contrary that fragmentation leads to extinction of all competitors but the one with the lowest diffusion rate. Ecologically, strong competition occurs for instance when resources are rare. Mathematically, it is known to lead indeed to spatial segregation, or in other words pattern formation, in homogeneous domains with appropriate boundary conditions or initial conditions (see for instance [6, 7, 11] and references therein). As such, our result can be seen as a contribution to the overarching research program on pattern formation in strongly competing systems and as one of the first results in spatially heterogeneous domains.

It is worthy to recall that by a result of Berestycki–Hamel–Rossi [5, Proposition 6.6], the periodic principal eigenvalue of a self-adjoint periodic scalar elliptic operator coincides with the decreasing limit as $R \rightarrow +\infty$ of its Dirichlet principal eigenvalue in the ball $(-R, R)$. Consequently, if the domain of a linearly stable in both senses, periodic, sign-changing steady state solution z of (1.4) is restricted to a periodicity cell $(y, y + L)$ with y chosen so that $z(y) = 0$, then we obtain a steady state for the corresponding Dirichlet problem which is linearly stable in the following senses:

$$\lambda_{1, \text{Dir}} \left(-\frac{d^2}{dx^2} - f_1[z], (y, y + L) \right) > 0,$$

$$\lambda_{1, \text{Dir}} \left(-\hat{\sigma}(z) \frac{d^2}{dx^2} - \hat{\sigma}(z) f_1[z], (y, y + L) \right) > 0.$$

1.4. Further extensions: the Allen–Cahn equation. The particular shape of function f in (1.4) is due to the biological considerations that have motivated this work. With very few modifications Theorem 1.1 can be extended to the case of the more familiar Allen–Cahn equation in periodic media

$$\partial_t z - \partial_{xx} z = \mu_L(x)(1 - z^2)z.$$

Here we can consider for instance $\mu_{|[0,1]} = \mathbf{1}_{[0,1/4] \cup [1/2,3/4]}$ and thus construct an oscillating and linearly stable steady state of the previous equation for any L larger than the threshold \underline{L} .

Structure of the paper. In Section 2, we prove Theorem 1.1, focusing first on the construction of v and then using the implicit function theorem to obtain the open neighborhood U . In Section 3, we prove Theorem 1.3 thanks to Theorem 1.1 and topological arguments.

2. THE SEGREGATED BISTABLE EQUATION

Our goal in this section is to prove that (1.4) admits sign-changing solutions that are also stable in the sense of (1.1) and (1.2).

Before going any further, we observe the following: replacing $(\frac{\mu_1}{\alpha}, \frac{\mu_2}{d^2})$ by (μ_1, μ_2) , (1.4) reads

$$(2.1) \quad -z'' = \mu_1(\alpha - z)z^+ - \mu_2(d + z)z^-.$$

Hence up to end of this section we have in mind the above more compact form. The piecewise-constant functions μ_1^* and μ_2^* defined in the introduction are accordingly modified, with $(\frac{M_1}{\alpha}, \frac{M_2}{d^2})$ replaced by (M_1, M_2) .

In order to construct a sign-changing, periodic and stable solution to (2.1), we need a preliminary result concerning its linearization.

2.1. Linearization near a non-constant stationary solution. Since the right hand side of (2.1) is only Lipschitz continuous at $z = 0$, we need some caution in order to properly introduce the linearization of the equation around a sign-changing steady state. Many authors have already addressed similar issues (see, for instance, [11, Section 4.1]). Since we could not find the precise statement that we needed, we decided to present a complete proof. We wish to point out that the result can be adapted to more general equations (for instance bounded domains with Neumann boundary conditions).

For all $(\mu_1, \mu_2, z) \in (L_{L\text{-per}}^\infty)^2 \times H_{L\text{-per}}^2$, we define

$$\mathcal{F} : (L_{L\text{-per}}^\infty)^2 \times H_{L\text{-per}}^2 \rightarrow L_{L\text{-per}}^2$$

such that, for all test functions $\varphi \in H_{L\text{-per}}^2$,

$$(2.2) \quad \langle \mathcal{F}(\mu_1, \mu_2, z), \varphi \rangle = \int_0^L z' \varphi' - \int_0^L (\mu_1(\alpha - z)z^+ - \mu_2(d + z)z^-) \varphi.$$

We recall that, by Sobolev embedding, the inclusion $H_{L\text{-per}}^2 \hookrightarrow \mathcal{C}_{L\text{-per}}^{1, \frac{1}{2}}$ holds true.

Lemma 2.1. *Let $O \subset H_{L\text{-per}}^2$ be an open set in the topology of $H_{L\text{-per}}^2$ such that for all $z \in O$, the closed set $z^{-1}(\{0\})$ has zero Lebesgue measure.*

Then $\mathcal{F} \in \mathcal{C}^1((L_{L\text{-per}}^\infty)^2 \times O, L_{L\text{-per}}^2)$.

For any $(\mu_1, \mu_2, z) \in (L_{L\text{-per}}^\infty)^2 \times O$ and any $(\eta_1, \eta_2, w) \in (L_{L\text{-per}}^\infty)^2 \times H_{L\text{-per}}^2$, the differential $d\mathcal{F}[\mu_1, \mu_2, z]$ evaluated at (η_1, η_2, w) is

$$\begin{aligned} \varphi \mapsto & \int_0^L w' \varphi' - \int_0^L (\eta_1 (\alpha - z) z^+ - \eta_2 (d + z) z^-) \varphi \\ & - \int_0^L (\mu_1 (\alpha - 2z) \mathbf{1}_{z>0} + \mu_2 (d + 2z) \mathbf{1}_{z<0}) w \varphi. \end{aligned}$$

Remark. Some assumptions on the open set O are necessary. In general, the Gâteaux differential of \mathcal{F} at (μ_1, μ_2, z) in the direction (η_1, η_2, w) fails to be linear with respect to (η_1, η_2, w) . More precisely, it is the sum of the linear functional above and of

$$\varphi \mapsto - \int_0^L (\mu_1 \alpha w^+ - \mu_2 d w^-) \mathbf{1}_{z=0} \varphi,$$

which is non-linear with respect to w . We can prove this by partitioning $\mathbb{R} = \{z > 0\} \cup \{z = 0\} \cup \{z < 0\}$.

Proof. The linear mapping appearing in the statement above is readily continuous. Thus we only need to show that it is indeed the Gâteaux differential.

Fix $(\mu_1, \mu_2, z) \in (L_{L\text{-per}}^\infty)^2 \times O$ and $(\eta_1, \eta_2, w) \in (L_{L\text{-per}}^\infty)^2 \times H_{L\text{-per}}^2$. For all $t > 0$ and all $\varphi \in H_{L\text{-per}}^2$,

$$\begin{aligned} & \frac{1}{t} (\mathcal{F}[(\mu_1, \mu_2, z) + t(\eta_1, \eta_2, w)] - \mathcal{F}[(\mu_1, \mu_2, z)])(\varphi) = \\ & \int_0^L w' \varphi' - \frac{1}{t} \int_0^L ((\mu_1 + t\eta_1) (\alpha - (z + tw)) (z + tw)^+ - \mu_1 (\alpha - z) v^+) \varphi \\ & \quad + \frac{1}{t} \int_0^L ((\mu_2 + t\eta_2) (d + (z + tw)) (z + tw)^- - \mu_2 (d - z) z^-) \varphi. \end{aligned}$$

The first term in the right hand side does not depend on t . We only need to consider the second one, as the third one can be dealt with in a similar way. Rearranging the terms, we find

$$\begin{aligned} & \frac{1}{t} \int_0^L ((\mu_1 + t\eta_1) (\alpha - (z + tw)) (z + tw)^+ - \mu_1 (\alpha - z) v^+) \varphi \\ & = \int_0^L \eta_1 (\alpha - (z + tw)) (z + tw)^+ \varphi \\ & \quad + \int_0^L \mu_1 \frac{(\alpha - (z + tw)) (z + tw)^+ - (\alpha - z) v^+}{t} \varphi. \end{aligned}$$

The dominated convergence theorem yields

$$\int_0^L \eta_1 (\alpha - (z + tw)) (z + tw)^+ \varphi \rightarrow \int_0^L \eta_1 (\alpha - z) v^+ \varphi \quad \text{as } t \rightarrow 0.$$

Rearranging the last term of the preceding equality, we find

$$\begin{aligned} \int_0^L \mu_1 \left(\frac{(\alpha - z - tw)(z + tw)^+ - (\alpha - z)z^+}{t} \right) \varphi \\ = \int_0^L \mu_1 \left(\frac{(z + tw)^+ - z^+}{t} \right) (\alpha - z) \varphi - \int_0^L \mu_1 w \alpha (z + tw)^+ \varphi. \end{aligned}$$

By dominated convergence,

$$\lim_{t \rightarrow 0} \int_0^L \mu_1 w \alpha (z + tw)^+ \varphi = \int_0^L \mu_1 w \alpha z^+ \varphi.$$

Since by assumption $z^{-1}(\{0\})$ has zero Lebesgue measure and the map $\zeta \mapsto \zeta^+$ is smooth away from 0, the dominated convergence theorem yields once again

$$\lim_{t \rightarrow 0} \int_0^L \mu_1 \left(\frac{(z + tw)^+ - z^+}{t} \right) (\alpha - z) \varphi = \int_0^L \mu_1 w \mathbf{1}_{z>0} (\alpha - z) \varphi.$$

This concludes the proof. \square

2.2. Construction of the solution. We now proceed by constructing the solution of (2.1). To do so, we first consider the equation with piecewise-constant coefficients. In this case, solutions can be constructed by gluing together different profiles. The implicit function theorem then leads to an open neighborhood of valid coefficients near this piecewise-constant pair.

2.2.1. Piecewise-constant coefficients. In the following result we collect some properties of the solutions of the logistic equation with non-zero Dirichlet conditions. These properties are well known and straightforward consequences of the comparison principle. For this reason, we do not present here a fully detailed proof.

Lemma 2.2. *For all $A > 0$, $M > 0$, $\nu \in [\frac{1}{2}, 1)$ and $R > 0$ there exists a unique positive solution $w_{A,M,\nu,R} \in \mathcal{C}^2([-R, R])$ of*

$$\begin{cases} -w'' = M(A - w)w & \text{in } (-R, R) \\ w(\pm R) = \nu A. \end{cases}$$

The function $w_{A,M,\nu,R}$ is even and satisfies

$$\nu A < w_{A,M,\nu,R}(x) < A \quad \text{for all } x \in (-R, R).$$

Furthermore, let

$$\Phi : (A, M, \nu, R) \mapsto w'_{A,M,\nu,R}(-R).$$

The following properties hold true.

- (1) Φ is a positive and continuous;
- (2) it holds

$$\lim_{R \rightarrow 0^+} \Phi(A, M, \nu, R) = 0;$$

- (3) there exists $\gamma_{A,M,\nu} \in (0, +\infty)$ such that

$$\gamma_{A,M,\nu} = \lim_{R \rightarrow +\infty} \Phi(A, M, \nu, R).$$

Moreover, $(A, M, \nu) \mapsto \gamma_{A,M,\nu}$ is continuous with respect to A , M and ν , increasing with respect to A and M and decreasing with respect to ν . In particular $0 = \lim_{\nu \rightarrow 1} \gamma_{A,M,\nu} < \gamma_{A,M,\nu} < \gamma_{A,M,\frac{1}{2}}$;

- (4) the function $R \mapsto \Phi(A, M, \nu, R)$ is an increasing homeomorphism from $(0, +\infty)$ onto $(0, \gamma_{A, M, \nu})$;
- (5) the function $\nu \mapsto \Phi(A, M, \nu, R)$ is a decreasing homeomorphism from $[\frac{1}{2}, 1)$ onto $(0, \Phi(A, M, \frac{1}{2}, R)]$.

We point out that the upper limit $\gamma_{A, M, \nu}$ can actually be determined explicitly.

Proof. We perform the following change of variables

$$w(x) = AW_{\rho, \nu} \left(\sqrt{AM}x \right) \quad \text{and} \quad \rho = \sqrt{AM}R.$$

Here the function $W_{\rho, \nu}$ is a solution to the scaled equation

$$(2.3) \quad \begin{cases} -W'' = (1 - W)W & \text{in } (-\rho, \rho) \\ W(\pm\rho) = \nu. \end{cases}$$

We can rephrase all the statements of the result in terms of the dependence of $W_{\rho, \nu}$ on ρ and ν . Here we consider only the dependence on ρ . The same arguments can be adapted to show the corresponding results in terms of ν .

For any value of $\rho > 0$ and $\nu \in [\frac{1}{2}, 1)$, the previous equation admits a unique, positive solution which is even and is such that $\nu < W(x) < 1$ for all $x \in (-\rho, \rho)$. This follows by standard arguments. We just observe that the functions $x \mapsto \nu \cos(\gamma x) / \cos(\gamma \rho)$ are sub-solutions of (2.3) for γ small enough, while the constant 1 is always a super-solution.

Notice that, for all $\kappa > 1$:

$$-(\kappa W_{\rho, \nu})'' = (1 - W_{\rho, \nu}) \kappa W_{\rho, \nu} \geq (1 - \kappa W_{\rho, \nu}) \kappa W_{\rho, \nu} \text{ in } (-\rho, \rho).$$

For all $\rho' > \rho > 0$, the following quantity is well-defined:

$$\kappa^* = \inf \{ \kappa > 1 \mid \kappa W_{\rho', \nu} \geq W_{\rho, \nu} \text{ in } (-\rho, \rho) \}.$$

Assuming by contradiction that $\kappa^* > 1$ and applying the strong maximum principle, we get a contradiction. Hence the family $(W_{\rho, \nu})_{\rho > 0}$ is non-decreasing, and once more by the strong maximum principle, it is in fact increasing.

It follows that the function $\rho \mapsto \max_{[-\rho, \rho]} W_{\rho, \nu}(x)$ is increasing with limit 1 as $\rho \rightarrow +\infty$. By classical elliptic estimates (see Gilbarg–Trudinger [17]) the family converges locally uniformly to a bounded and positive solution of (2.3) defined on the whole line \mathbb{R} . Hence, as $\rho \rightarrow +\infty$, we find that $W_{\rho, \nu} \rightarrow 1$ locally in \mathcal{C}^2 .

We now consider the shifted family of functions

$$\overline{W}_{\rho, \nu}(x) = W_{\rho, \nu}(x - \rho) \quad \text{for } x \in [0, 2\rho].$$

The family $\rho \mapsto \overline{W}_{\rho, \nu}$ is increasing. In particular, by the Hopf lemma,

$$\rho \mapsto \overline{W}'_{\rho, \nu}(0)$$

is increasing as well. Once again, classical elliptic estimates show that, as $\rho \rightarrow +\infty$, the family $\overline{W}_{\rho, \nu}$ converges locally uniformly to the unique solution \overline{W} of

$$(2.4) \quad \begin{cases} -\overline{W}'' = (1 - \overline{W})\overline{W} & \text{in } (0, +\infty) \\ \overline{W}(0) = \nu \\ \nu < \overline{W} < 1 & \text{in } (0, +\infty) \end{cases}$$

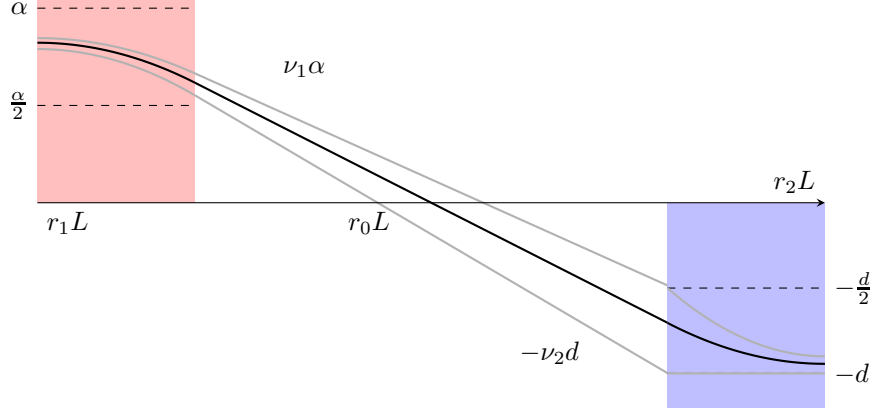


FIGURE 2.1. Visual representation of the construction of v . In red, areas where $\mu_1^L = M_1$. In blue, areas where $\mu_2^L = M_2$. In gray, the bounds given by $\underline{\nu}_L$ and $\overline{\nu}_L$. In black, the solution v .

(see Du–Lin [14, 15, Proposition 4.1]). Thus, the limit as $\rho \rightarrow +\infty$ of $\overline{W}'_{\rho, \nu}(-\rho)$ is finite and positive. We can figure out its value by testing (2.4) against \overline{W}' . This yields the identity

$$\lim_{\rho \rightarrow +\infty} \overline{W}'_{\rho, \nu}(-\rho) = \sqrt{\frac{1}{3} + \nu^2 \left(\frac{2}{3} \nu - 1 \right)}.$$

Observe that the limit is always positive and bounded.

We conclude by observing that the continuity of $\overline{W}'_{\rho, \nu}$ with respect to ρ is a classical consequence of the uniqueness of $\overline{W}_{\rho, \nu}$ and of compactness arguments. \square

From the previous result we deduce a property which is crucial for our construction. For sake of brevity, from now on we will simply write

$$\Phi_1(\nu, L) = \Phi(\alpha, M_1, \nu, r_1 L),$$

$$\Phi_2(\nu, L) = \Phi(d, M_2, \nu, r_2 L),$$

(recalling that $M_1 > 0$, $M_2 > 0$, $r_1 > 0$ and $r_2 > 0$ were fixed in the introduction).

We can finally construct the periodic stable solutions of (2.1) with the piecewise-constant coefficients.

Proposition 2.3. *There exists $\underline{L} > 0$ such that, for any $L > \underline{L}$, (2.1) with either $(\mu_1, \mu_2) = (\mu_1^L, \mu_2^L)$ or with $(\mu_1, \mu_2) = (\mu_1^L + \mu_2^L, \mu_1^L + \mu_2^L)$ admits a nonzero sign-changing solution $v \in H_{L\text{-per}}^2$ satisfying, for all L -periodic test functions $\varphi \in H_{L\text{-per}}^1$,*

$$\int_0^L v' \varphi' = \int_0^L (\mu_1 (\alpha - v) v^+ - \mu_2 (d + v) v^-) \varphi.$$

Furthermore, v is linearly stable in the sense of (1.1) and (1.2).

Proof. Let

$$\delta : (\nu, L) \mapsto -\Phi_1(\nu, L) r_0 L + \alpha \nu.$$

The function $\nu \mapsto \delta(\nu, L)$ is, for all $L > 0$, an increasing homeomorphism from $[\frac{1}{2}, 1)$ onto

$$\left[-\Phi_1\left(\frac{1}{2}, L\right) r_0 L + \frac{\alpha}{2}, \alpha \right).$$

Since $L \mapsto -\Phi_1\left(\frac{1}{2}, L\right) r_0 L$ is decreasing and goes to $-\infty$ as $L \rightarrow +\infty$, we can define the unique $L_0 > 0$ satisfying

$$-\Phi_1\left(\frac{1}{2}, L_0\right) r_0 L_0 + \frac{\alpha}{2} = -d.$$

Then for all $L > L_0$, we can define the unique $\underline{\nu}_L \in (\frac{1}{2}, 1)$ and the unique $\overline{\nu}_L \in (\underline{\nu}_L, 1)$ satisfying respectively

$$\delta(\underline{\nu}_L, L) = -d \text{ and } \delta(\overline{\nu}_L, L) = -\frac{d}{2}.$$

Now let

$$\psi : (\nu, L) \mapsto \Phi_1(\nu, L) - \Phi_2\left(-\frac{\delta(\nu, L)}{d}, L\right),$$

well-defined in $(\underline{\nu}_L, \overline{\nu}_L]$ for all $L > L_0$. For all $L > L_0$, $\nu \mapsto \psi(\nu, L)$ is a decreasing homeomorphism satisfying

$$\lim_{\nu \rightarrow \underline{\nu}_L} \psi(\nu, L) = \frac{\alpha \underline{\nu}_L + d}{r_0 L} > 0,$$

$$\psi(\overline{\nu}_L, L) = \frac{\alpha \overline{\nu}_L + \frac{d}{2}}{r_0 L} - \Phi_2\left(\frac{1}{2}, L\right).$$

Since $L \mapsto \psi(\overline{\nu}_L, L)$ goes to $-\gamma_{d, M_2, \frac{1}{2}} < 0$ as $L \rightarrow +\infty$, we can define $\underline{L} \geq L_0$ such that, for all $L > \underline{L}$,

$$\psi(\overline{\nu}_L, L) < 0$$

and deduce that for all $L > \underline{L}$, there exists a unique $\nu_L \in (\underline{\nu}_L, \overline{\nu}_L)$ satisfying $\psi(\nu_L, L) = 0$, that is

$$\Phi_1(\nu_L, L) = \Phi_2\left(-\frac{\delta(\nu_L, L)}{d}, L\right).$$

Next, we fix $L > \underline{L}$ and define $w_1 = w_{\alpha, M_1, \nu_L, r_1 L}$, $w_2 = w_{d, M_2, -d^{-1}\delta(\nu_L, L), r_2 L}$ as well as the nonzero, sign-changing, L -periodic function v by

$$v|_{[0, L)}(x) = \begin{cases} w_1(x) & \text{if } x \in [0, r_1 L) \\ -\Phi_1(\nu_L, L)(x - r_1 L) + \nu_L \alpha & \text{if } x \in [r_1 L, r_1 L + r_0 L) \\ w_2(x - r_1 L - r_0 L - r_2 L) & \text{if } x \in [r_1 L + r_0 L, r_1 L + r_0 L + 2r_2 L) \\ \Phi_1(\nu_L, L)(x - L + r_1 L) + \nu_L \alpha & \text{if } x \in [r_1 L + r_0 L + 2r_2 L, r_1 L + 2r_0 L + 2r_2 L) \\ w_1(x - L) & \text{if } x \in [r_1 L + 2r_0 L + 2r_1 L, L) \end{cases}$$

Since, by construction, v is a $\mathcal{C}_{L\text{-per}}^{1,1} \subset H_{L\text{-per}}^2$ juxtaposition of piecewise solutions of (2.1), we readily deduce that it is a solution of (2.1).

Regarding the stability of the solution v , from Lemma 2.1 we evince that the linearized elliptic operator at v , denoted $\mathcal{L} \in L(H_{L\text{-per}}^2, L_{L\text{-per}}^2)$, is

$$\mathcal{L} : \eta \mapsto \eta'' + [\mu_1(\alpha - 2v) \mathbf{1}_{v>0} + \mu_2(d + 2v) \mathbf{1}_{v<0}] \eta.$$

First we verify the stability in the sense of (1.1). Let λ be the corresponding periodic principal eigenvalue and $\psi \in H_{L\text{-per}}^2$ be the associated unique periodic positive eigenfunction, normalized in $L^2((0, L))$. From the identity

$$\int_0^L (-\mathcal{L}\psi - \lambda\psi) \psi = 0$$

we deduce

$$\begin{aligned} \int_0^L (\psi')^2 &= \int_0^L [\mu_1(\alpha - 2v) \mathbf{1}_{v>0} + \mu_2(d + 2v) \mathbf{1}_{v<0}] \psi^2 + \lambda \\ &= M_1 \int_{\{\mu_1>0\} \cap \{v>0\}} (\alpha - 2v) \psi^2 + M_2 \int_{\{\mu_2>0\} \cap \{v<0\}} (d + 2v) \psi^2 + \lambda. \end{aligned}$$

Since by construction

$$v \geq \nu_L \alpha > \frac{\alpha}{2} \text{ in } \{\mu_1 > 0\} \cap \{v > 0\}$$

and

$$v \leq -\left(-\frac{\delta(\nu_L, L)}{d}\right) d < -\frac{d}{2} \text{ in } \{\mu_2 > 0\} \cap \{v < 0\},$$

we deduce

$$\lambda > \int_0^L (\psi')^2 > 0.$$

Similarly, we verify the stability of v in the sense of (1.2). The same computations as before lead us to the desired conclusion.

This concludes the proof of existence and stability of sign-changing solutions for piecewise-constant coefficients \square

Remark. Going carefully through the proof, using $\overline{\nu}_L < 1$ and assuming that \underline{L} is minimal, we obtain the estimate $\underline{L} < L^*$, where $L^* > 0$ is the unique solution of

$$\Phi_2\left(\frac{1}{2}, L^*\right) L^* = \frac{1}{r_0} \max\left(\alpha + \frac{d}{2}, \frac{\alpha}{2} + d\right).$$

Hence estimating \underline{L} is only a matter of estimating $L \mapsto \Phi_2\left(\frac{1}{2}, L\right)$. Unfortunately, being unable to find any satisfying estimation of Φ_2 , we do not pursue further.

2.2.2. With regular coefficients. The function v constructed in Proposition 2.3 is linear around $v = 0$. Thus there exists an open neighborhood $O \subset H_{L\text{-per}}^2$ satisfying the assumptions of Lemma 2.1.

Proposition 2.4. *Under the assumptions of Proposition 2.3, for any $L > \underline{L}$ there exists an open neighborhood $U \subset (L_{L\text{-per}}^\infty)^2$ of (μ_1, μ_2) such that for all $(\rho_1, \rho_2) \in U$, (2.1) with (ρ_1, ρ_2) admits a sign-changing, L -periodic, weak solution. The solution is also linearly stable in the sense of (1.1) and (1.2).*

Proof. Let $L > \underline{L}$ and let $(\mu_1, \mu_2, v) \in (L_{L\text{-per}}^\infty)^2 \times H_{L\text{-per}}^2$ be the solution constructed in Proposition 2.3.

The prerequisites of the implicit function theorem are readily satisfied for the functional \mathcal{F} at (μ_1, μ_2, v) . In particular, since the solution v is linearly stable in the sense of (1.1), the functional $\frac{\partial \mathcal{F}}{\partial z}[\mu_1, \mu_2, v]$ is invertible in the following sense: for all $f \in L_{L\text{-per}}^2$, there exists a unique weak solution $z_f \in H_{L\text{-per}}^2$ of

$$\frac{\partial \mathcal{F}}{\partial v}[\mu_1, \mu_2, z](z_f) = f.$$

This follows by standard regularity results.

By virtue of the implicit function theorem, there exists an open neighborhood $U \subset (L_{L\text{-per}}^\infty)^2$ of (μ_1, μ_2) , an open neighborhood $V \subset O \subset H_{L\text{-per}}^2$ of v and a \mathcal{C}^1 diffeomorphism $\Psi : U \rightarrow V$ such that, for all $(\rho_1, \rho_2) \in U$,

$$\mathcal{F}[\rho_1, \rho_2, \Psi[\rho_1, \rho_2]] = 0.$$

Finally, since the map Ψ is \mathcal{C}^1 , we find that the linear stability of the solution is preserved in a open neighborhood of (μ_1, μ_2) . \square

2.3. Uniqueness. We end this section with the following uniqueness result, which will be used later on. We emphasize that this is not a full uniqueness result.

Lemma 2.5. *Let $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, $L > \underline{L}$, $(\mu_1, \mu_2) \in U$ and v be the solution of (2.1) given by Proposition 2.4.*

Then any solution z of (2.1) satisfying

$$z^+ > \varepsilon_1 v^+ \text{ and } z^- > \varepsilon_2 v^-$$

coincides with v .

Proof. Let z be any such solution. By continuity of z and by the fact that z admits only one zero in each periodicity cell, the condition of the statement directly guarantees that $\{z > 0\} = \{v > 0\}$, $\{z < 0\} = \{v < 0\}$ and $\{z = 0\} = \{v = 0\}$.

Now we focus on one connected component of, say, $\{v > 0\}$. By translation, we can assume without loss of generality that this interval has the form $(0, R)$ with $R < L$. The functions $z|_{(0,R)}$ and $v|_{(0,R)}$ are then both solutions of the following Dirichlet problem:

$$\begin{cases} -z'' = \mu_1(1-z)z & \text{in } (0, R) \\ z(0) = z(R) = 0. \end{cases}$$

Since it is well-known that such a solution is unique (we refer for instance to Berestycki [2]), we deduce that z and v coincide in any connected component of $\{v > 0\}$.

Repeating subsequently the argument in $\{v < 0\}$, we obtain the claimed uniqueness. \square

3. THE STRONGLY COMPETITIVE COMPETITION-DIFFUSION SYSTEM

In the previous section we have considered the equation

$$-z'' = \frac{\mu_1}{\alpha}(\alpha - z)z^+ - \frac{\mu_2}{d^2}(d + z)z^-.$$

For this equation and particular choices of μ_1 and μ_2 , we have constructed a sign-changing solution $v \in \mathcal{C}_{L\text{-per}}^{1,1}$ for periods L greater than a threshold \underline{L} . We have also shown that this solution is linearly stable in the sense of (1.1) and (1.2).

In this section, we aim at using this result to prove the existence of linearly stable solutions of (1.5). Specifically, fixing $L > \underline{L}$ and a positive L -periodic smooth function ω , our aim is to prove that for any $k > 0$ large enough there exists a positive and stable solution of (1.5) $(u_{1,k}, u_{2,k}) \in \mathcal{C}_{L\text{-per}}^{1,1}$ such that

$$(u_{1,k}, u_{2,k}) \rightarrow \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \quad \text{as } k \rightarrow +\infty$$

in $H_{L\text{-per}}^1$ and $\mathcal{C}_{L\text{-per}}^{0,\gamma}$ for $\gamma \in (0, \frac{1}{2})$.

We will show the result in a series of steps: first, we give some *a priori* estimates of the solution of a more general class of systems. Then, by means of topological

arguments, we deduce from these estimates the existence of solutions. Finally we establish the uniqueness and the linear stability of the solutions.

3.1. *A priori estimate.* We start by showing *a priori* estimates for the solutions of a family of systems that contains (1.5) as a special case. We are here interested in the L -periodic positive solutions of

$$(3.1) \quad \begin{cases} -u_1'' = \mu_1(x)(1 - u_1)u_1 - k\omega(x)u_1 \left[tu_2 + (1 - t)\frac{v^-}{d} \right] \\ -du_2'' = \mu_2(x)(1 - u_2)u_2 - \alpha k\omega(x)u_2 \left[tu_1 + (1 - t)\frac{v^+}{\alpha} \right] \end{cases}$$

where $k > 0$ and $t \in [0, 1]$. Observe that if we take $t = 1$, then (3.1) reduces to the original system (1.5). On the contrary, if $t = 0$, the equations in (3.1) are decoupled.

Lemma 3.1. *There exists a constant $C > 0$, independent of $k > 0$ and $t \in [0, 1]$, such that if $(u_1, u_2) \in \mathcal{C}_{L\text{-per}}^{1,1}$ is a solution of (3.1) with*

$$u_1 > \frac{v^+}{2\alpha} \quad \text{and} \quad u_2 > \frac{v^-}{2d},$$

then

$$\|(u_1, u_2)\|_{H_{L\text{-per}}^1} + \|(u_1, u_2)\|_{\mathcal{C}_{L\text{-per}}^{0, \frac{1}{2}}} \leq C.$$

Let $((u_{1,k}, u_{2,k}))_k$ be any sequence of solutions as before, with $k \rightarrow +\infty$ and $t = t_k \in [0, 1]$. Then

$$(u_{1,k}, u_{2,k}) \rightarrow \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \quad \text{as } k \rightarrow +\infty$$

in $H_{L\text{-per}}^1$ and in $\mathcal{C}^{0,\gamma}$ for any $\gamma \in (0, \frac{1}{2})$.

Proof. We first observe that if (u_1, u_2) is a non-negative solution of (3.1) then, by the maximum principle, $0 < u_1 < 1$ and $0 < u_2 < 1$.

We now consider the equation in u_1 in (3.1). By testing the equation against u_1 itself, we find

$$\int_0^L (u_1')^2 + \mu_1 u_1^3 + k\omega u_1^2 \left[tu_2 + (1 - t)\frac{v^-}{d} \right] \leq \int_0^L \mu_1 u_1^2 \leq C$$

where the constant $C > 0$ can be chosen independently of t and k . Thus u_1 is uniformly bounded in $H_{L\text{-per}}^1$ and, by Sobolev's embeddings, u_1 is also uniformly bounded in $\mathcal{C}_{L\text{-per}}^{0, \frac{1}{2}}$. We can argue similarly for the component u_2 .

Let us now consider a sequence of solutions $((u_{1,k}, u_{2,k}))_k$ as in the statement, with $k \rightarrow +\infty$. By testing the equation in $u_{1,k}$ against $\left(u_{1,k} - \frac{v^+}{\alpha}\right) \in H_{L\text{-per}}^1$, we obtain

$$\begin{aligned} \int_0^L u_{1,k}' \left(u_{1,k} - \frac{v^+}{\alpha} \right)' + k\omega u_{1,k} \left(u_{1,k} - \frac{v^+}{\alpha} \right) \left[tu_{2,k} + (1 - t)\frac{v^-}{d} \right] \\ = \int_0^L \mu_1 (1 - u_{1,k}) u_{1,k} \left(u_{1,k} - \frac{v^+}{\alpha} \right). \end{aligned}$$

After some simple algebraic manipulations, this yields

$$(3.2) \quad \int_0^L \left[\left(u_{1,k} - \frac{v^+}{\alpha} \right) \right]^2 + k\omega \left(u_{1,k} - \frac{v^+}{\alpha} \right)^2 \frac{v^-}{2d} \\ \leq \int_0^L \left(\frac{v^+}{\alpha} \right)' \left(u_{1,k} - \frac{v^+}{\alpha} \right)' + \int_0^L \mu_1(1 - u_{1,k})u_{1,k} \left(u_{1,k} - \frac{v^+}{\alpha} \right).$$

By the uniform $H_{L\text{-per}}^1(\mathbb{R})$ estimates, we know that the right hand-side is bounded uniformly in k and t . Thus, if \bar{u}_1 is any limit of $(u_{1,k})_k$ (weak in $H_{L\text{-per}}^1$ and in $\mathcal{C}_{L\text{-per}}^{0,\gamma}$ for any $\gamma \in (0, \frac{1}{2})$), we find

$$\left(\bar{u}_1 - \frac{v^+}{\alpha} \right)^2 v^- = 0 \quad \text{a.e. in } \mathbb{R}$$

that is $\bar{u}_1 = \frac{v^+}{\alpha} = 0$ where $v^- > 0$. Since by assumption $\bar{u}_1 > \frac{v^+}{2\alpha}$, by Lemma 2.5, it must be $\bar{u}_1 = \frac{v^+}{\alpha}$.

Going back to (3.2), the right hand side converges to 0 as $k \rightarrow +\infty$, which implies the strong convergence in $H_{L\text{-per}}^1$ of a subsequence of $(u_{1,k})_k$. We conclude the proof by pointing out that the same reasoning holds for any subsequence of $(u_{1,k})_k$. As a result we deduce the strong convergence of the whole original sequence of solutions. \square

An interesting consequence of the previous result is that the solutions of (3.1), when k is large, are close to the segregated state $\left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right)$, independently of the value of $t \in [0, 1]$. More precisely, we have the following corollary.

Corollary 3.2. *For all $\gamma \in (0, \frac{1}{2})$ and $\varepsilon > 0$, there exists $\bar{k} = \bar{k}(\gamma, \varepsilon) > 0$ such that, for all $t \in [0, 1]$, $k > \bar{k}$ and $(u_1, u_2) \in \mathcal{C}_{L\text{-per}}^{1,1}$ solution of (3.1) such that*

$$u_1 > \frac{v^+}{2\alpha} \quad \text{and} \quad u_2 > \frac{v^-}{2d},$$

we have

$$\left\| (u_1, u_2) - \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \right\|_{H_{L\text{-per}}^1} + \left\| (u_1, u_2) - \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \right\|_{\mathcal{C}_{L\text{-per}}^{0,\gamma}} \leq \varepsilon.$$

3.2. Existence of solutions. We now show the existence of solution of (1.5) when k is large. We will prove this result in two steps, first proving the existence of solutions of an auxiliary problem, and then, making use of a homotopy argument, we will transfer this result to the original problem. Our argument is inspired by the method proposed in [10] to prove the existence of solutions of a related problem.

Lemma 3.3. *For any $k > 0$, there exists a unique positive solution $(u_1, u_2) \in \mathcal{C}_{L\text{-per}}^{1,1}$ of*

$$(3.3) \quad \begin{cases} -u_1'' = \mu_1(1 - u_1)u_1 - k\omega u_1 \frac{v^-}{d} \\ -du_2'' = \mu_2(1 - u_2)u_2 - \alpha k\omega u_2 \frac{v^+}{\alpha}. \end{cases}$$

Furthermore, the solution is linearly stable, $u_1 > \frac{v^+}{\alpha}$ and $u_2 > \frac{v^-}{d}$.

Proof. Since the equations in the system are actually decoupled, we can consider them one at a time. Thus, we show the proof only for the component u_1 . We can apply the same reasoning to the equation in u_2 .

We consider the equation

$$(3.4) \quad -u_1'' = \left[\left(\mu_1 - k\omega \frac{v^-}{d} \right) - \mu_1 u_1 \right] u_1$$

with periodicity conditions. We observe that $\frac{v^+}{\alpha}$ is a sub-solution whereas 1 is a super-solution, so that there exists indeed a solution u of (3.4) satisfying $\frac{v^+}{\alpha} < u_1 < 1$. Moreover, (3.4) falls in the general theory of periodic KPP reaction–diffusion equations developed by Berestycki–Hamel–Roques in [4]. In particular, it follows that the solution u_1 is unique, periodic and linearly stable [4, Theorem 2.4]. \square

We now pass to the second step of the construction. For notation convenience, let $X = \mathcal{C}_{L\text{-per}}^{0,1/4}$ (any Hölder exponent $\gamma \in (0, \frac{1}{2})$ would do) and let $L \in \mathcal{K}(X; X)$ be the linear compact operator defined as

$$z = Lf \iff \begin{cases} -z'' + z = f \\ \text{with } z, f \in X. \end{cases}$$

We consider the homotopy $H : X^2 \times [0, 1] \rightarrow X^2$, defined by

$$H(u_1, u_2; t) = \begin{cases} u_1 - L \left(u_1 + \mu_1(1 - u_1)u_1 - k\omega u_1 \left[tu_2 + (1 - t)\frac{v^-}{d} \right] \right) \\ u_2 - \frac{1}{d}L \left(du_2 + \mu_2(1 - u_2)u_2 - \alpha k\omega u_2 \left[tu_1 + (1 - t)\frac{v^+}{\alpha} \right] \right). \end{cases}$$

Observe that the homotopy H is of the form $\text{Id} - K_t$ where $\text{Id} : X^2 \rightarrow X^2$ is the identity operator, and $K_t \in \mathcal{K}(X^2 \times [0, 1]; X^2)$ is a compact operator for any $t \in [0, 1]$ and is continuous in t by standard elliptic estimates. In this regard, we observe that k is fixed.

We have that $H(u_1, u_2; 0) = 0$ if and only if (u_1, u_2) are solutions of (3.3), while $H(u_1, u_2; 1) = 0$ if and only if (u_1, u_2) are solutions of (1.5). Our goal is to apply the theory of the Leray-Schauder degree in order to evince the existence of solutions of (1.5) from the existence of solutions of (3.3), Lemma 3.3.

Let $O_\varepsilon \subset X^2$ be the connected open subset of X^2 defined as the set of all $(u_1, u_2) \in X^2$ such that

$$\frac{v^+}{2\alpha} < u_1 < 1, \quad \frac{v^-}{2d} < u_2 < 1, \quad \left\| (u_1, u_2) - \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \right\|_{X^2} < \varepsilon.$$

Lemma 3.4. *For any $\varepsilon > 0$ there exists $\bar{k} > 0$ such that the equation*

$$H(u_1, u_2; t) = 0$$

has no solutions for any $t \in [0, 1]$ and $k \geq \bar{k}$ on ∂O_ε .

This result follows directly from Corollary 3.2.

Lemma 3.5. *The equation*

$$H(u_1, u_2; 0) = 0$$

has a unique solution in O_ε . Moreover there exists $\bar{k} > 0$ such that if $k \geq \bar{k}$, then such solution has fixed point index 1, that is

$$\text{index}_{X^2}(O_\varepsilon; (u_1, u_2)) = 1.$$

This result follows from Lemma 3.3. We also recall that the fixed point index of isolated solution can be computed by linearization if the equation involves \mathcal{C}^1 operators, [1, Theorem 4.2.11].

We can thus conclude by virtue of the Leray–Schauder theorem (see [21] and [1, Theorem 4.3.4]).

Lemma 3.6. *For any $\varepsilon > 0$, there exists $\bar{k} > 0$ such that, for all $k > \bar{k}$, (1.5) has a solution $(u_{1,k}, u_{2,k})$ in \mathcal{O}_ε . We have*

$$\lim_{k \rightarrow +\infty} \left\| (u_{1,k}, u_{2,k}) - \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \right\|_{H_{L\text{-per}}^1} + \left\| (u_{1,k}, u_{2,k}) - \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right) \right\|_{\mathcal{C}^{0,\gamma}} = 0$$

for any $\gamma \in (0, \frac{1}{2})$.

If needed, one can improve the convergence result, by stating that the solutions are uniformly bounded in the Lipschitz norm and converge in the $\mathcal{C}^{0,\gamma}$ norm for any $\gamma \in (0, 1)$. See, on this subject, the results in [6].

3.3. Linear stability for k large. We now investigate the linear stability of the solutions obtained in Lemma 3.6. To this end, we consider the linearized system (1.5) at the solution (u_1, u_2) and introduce its periodic principal eigenvalue.

For all $k > \bar{k}$, let

$$\lambda_{1,k} = \lambda_{1,L\text{-per}} \left(- \begin{pmatrix} \frac{d^2}{dx^2} + \mu_1(1 - 2u_{1,k}) - k\omega u_{2,k} & k\omega u_{1,k} \\ \alpha k\omega u_{2,k} & d\frac{d^2}{dx^2} + \mu_2(1 - 2u_{2,k})\psi - \alpha k\omega u_{1,k} \end{pmatrix} \right)$$

and assume that the associated periodic principal eigenfunction (φ_k, ψ_k) is normalized in such a way that

$$\max_{x \in [0, L]} (\alpha\varphi_k + d\psi_k)(x) = 1.$$

Observe that since both φ_k and ψ_k are positive, this automatically implies that the two functions are globally bounded.

We start by showing a priori estimates on the principal eigenvalue and the principal eigenfunctions.

Lemma 3.7. *The principal eigenvalues are uniformly bounded from below. There exists $C \in \mathbb{R}$ such that*

$$\lambda_{1,k} > -C \quad \text{for all } k > \bar{k}.$$

Proof. It suffices to take

$$C = \sup_{k > \bar{k}, x \in \mathbb{R}} (|\mu_1(1 - 2u_{1,k})| + |\mu_2(1 - 2u_{2,k})|).$$

Indeed, the solution $(u_{1,k}, u_{2,k}) \in \mathcal{O}_\varepsilon$ are uniformly bounded. Thus C is finite. We then consider the sum of the equation in $\alpha\varphi_k$ and in ψ_k . The conclusion follows from the fact that the equation

$$-(\alpha\varphi_k + d\psi_k)'' = \mu_1(1 - 2u_{1,k})\alpha\varphi_k + \mu_2(1 - 2u_{2,k})\psi_k + \lambda_{1,k}(\alpha\varphi_k + \psi_k),$$

where the right-hand side is smaller than or equal to $(C + \lambda_{1,k})(\alpha\varphi_k + \psi_k)$, has no positive L -periodic solution if $\lambda_{1,k} < -C$. \square

Lemma 3.8. *For any $\varepsilon > 0$ and $\delta > 0$, there exists $\bar{k} > 0$ such that*

$$\sup_{\{v^- > \varepsilon\}} \varphi_k + \sup_{\{v^+ > \varepsilon\}} \psi_k \leq \delta$$

for any $k \geq \bar{k}$.

Proof. We prove only the estimate in ψ_k , since the estimate in φ_k follows the same reasoning. Moreover we will implicitly prove the estimate in an interval of length L , and extend them by periodicity. By virtue of a scaling and a translation, we can also assume for simplicity that $\{v^+ > 0\} = (-1, 1)$.

By Lemma 3.6, we already know that

$$\omega(x)u_{1,k} > \omega(x)\frac{v^+}{2\alpha} \geq D(1-x^2)^+$$

for k large enough. Here $D > 0$ is a small constant independent of k . Plugging this information in (1.3), we find that

$$\begin{cases} -du_{2,k}'' + Dk(1-x^2)^+u_{2,k} \leq \mu_2(1-u_{2,k})u_{2,k} \leq G & \text{in } (-1, 1) \\ 0 < u_{2,k} < 1 \end{cases}$$

where

$$G = \sup_{k, x \in \mathbb{R}} \mu_2(1-u_{2,k})u_{2,k}$$

is by assumption a finite constant. We are then in position to apply the estimate in Lemma A.1. This yields

$$Dk(1-x^2)^+u_{2,k} \leq C\frac{1}{(1-x^2)^2} + 2G.$$

We now fix $\varepsilon > 0$ small. By the previous estimate we find that there exists $C_\varepsilon > 0$ such that

$$\sup_{x \in [-1+\frac{\varepsilon}{2}, 1-\frac{\varepsilon}{2}]} k\omega(x)u_{2,k} \leq C_\varepsilon.$$

From the equation in ψ_k , we deduce

$$\begin{cases} -d\psi_k'' + Dk(1-x^2)^+\psi_k \leq C & \text{in } (-1+\frac{\varepsilon}{2}, 1-\frac{\varepsilon}{2}) \\ 0 < \psi_k < \frac{1}{d} \end{cases}$$

for another constant $C > 0$ that does not depend on k . We can conclude by applying again Lemma A.1 to obtain the sought decay estimate of ψ_k in the interval $(-1+\varepsilon, 1-\varepsilon)$. \square

With the uniform estimates of Lemma 3.7 and Lemma 3.8 we are now in position to show that the solution (u_1, u_2) constructed in the previous section is indeed linearly stable if k is sufficiently large.

Of course, if $\liminf_{k \rightarrow +\infty} \lambda_{1,k} = +\infty$, then the proof is done. Hence we assume from now on that $\liminf_{k \rightarrow +\infty} \lambda_{1,k} < +\infty$. Up to extraction of a subsequence, we also assume that $\lambda_{1,k} \rightarrow \liminf_{k \rightarrow +\infty} \lambda_{1,k}$ as $k \rightarrow +\infty$. In particular, $(\lambda_{1,k})_k$ is bounded.

Lemma 3.9. *For all $k > \bar{k}$, we define $Z_k \in \mathcal{C}_{L\text{-per}}^{1,1}$ as*

$$Z_k = \alpha\varphi_k + d\psi_k.$$

Then the sequence of positive functions $(Z_k)_k$ is uniformly bounded in $W_{L\text{-per}}^{2,p}$ and $\mathcal{C}_{L\text{-per}}^{1,\gamma}$ for any $p < \infty$ and $\gamma < 1$. Each Z_k solves

$$-Z_k'' = \left[\mu_1 \left(1 - 2\frac{v^+}{\alpha} \right) + \frac{1}{d}\mu_2 \left(1 + 2\frac{v^-}{d} \right) \right] Z_k + \lambda_{1,k}\sigma(v)Z_k + o_k(1)$$

where $o_k(1)$ is a sequence of functions, bounded uniformly in L^∞ and such that $o_k(1) \rightarrow 0$ in $L_{L\text{-per}}^p$ for any $p < \infty$.

Proof. Once again, we take the sum of the equation in $\alpha\varphi_k$ and the equation in ψ_k . We thus find

$$(3.5) \quad -(\alpha\varphi_k + d\psi_k)'' = \mu_1(1 - 2u_{1,k})\alpha\varphi_k + \mu_2(1 - 2u_{2,k})\psi_k + \lambda_{1,k}(\alpha\varphi_k + \psi_k).$$

We observe that the terms in the right hand side of (3.5) are uniformly bounded. Thus there exists $Z \in (H^2 \cap \mathcal{C}^{1,\gamma})_{L\text{-per}}$ such that, up to subsequence, $Z_k \rightarrow Z \geq 0$. By uniform convergence we have $\max Z = 1$. As a consequence of Lemma 3.8, we also have that

$$(\alpha\varphi_k + \psi_k) \rightarrow \left(\mathbf{1}_{v>0} + \frac{1}{d}\mathbf{1}_{v<0} \right) Z = \sigma(v)Z$$

in L^p for any $p < \infty$.

We now rearrange the terms of (3.5) as follows:

$$\begin{aligned} -Z_k'' &= \left[\mu_1 \left(1 - 2\frac{v^+}{\alpha} \right) + \frac{1}{d}\mu_2 \left(1 + 2\frac{v^-}{d} \right) \right] Z_k + \lambda_{1,k}\sigma(v)Z_k \\ &\quad + \lambda_{1,k} [(\alpha\varphi_k + \psi_k) - \sigma(v)Z_k] \\ &\quad + \left[2\alpha\mu_1 \left(\frac{v^+}{\alpha} - u_{1,k} \right) \varphi_k - 2\mu_2 \left(\frac{v^-}{d} + u_{2,k} \right) \psi_k \right] \\ &\quad - \left(\mu_1 \left(1 - 2\frac{v^+}{\alpha} \right) d\psi_k + \frac{1}{d}\mu_2 \left(1 + 2\frac{v^-}{d} \right) \alpha\varphi_k \right). \end{aligned}$$

In order to conclude, we need to show that the second, third and fourth lines in the previous equation are small contributions in the $L_{L\text{-per}}^p$ norm. Now, we just proved that the second line converges to zero in the L^p topology. The third line also converges to zero, since $(u_1, u_2)_k \rightarrow \left(\frac{v^+}{\alpha}, \frac{v^-}{d} \right)$ in $\mathcal{C}^{0,\gamma}$. Finally, by Lemma 3.8, the fourth line also converges to zero in $L_{L\text{-per}}^p$. \square

We now recall that the solution v is, by construction, linearly stable in the sense of (1.2). This implies in particular that any eigenpair (λ, Z) satisfying

$$(3.6) \quad -Z'' - \left[\mu_1 \left(1 - 2\frac{v^+}{\alpha} \right) \mathbf{1}_{v>0} + \frac{1}{d}\mu_2 \left(1 + 2\frac{v^-}{d} \right) \mathbf{1}_{v<0} \right] Z = \lambda\sigma(v)Z$$

is such that λ has a positive real part. More precisely, using the uniqueness part of the Krein–Rutman theorem, we can establish the following convergence result.

Lemma 3.10. *There exists $\bar{k} > 0$ such that for any $k \geq \bar{k}$ the solution $(u_{1,k}, u_{2,k})$ is linearly stable.*

Furthermore, the sequence $((\lambda_{1,k}, Z_k))_k$ and the principal eigenpair (λ_1, Z) given by the notion of stability in the sense of (1.2) satisfy the following equalities:

$$\liminf_{k \rightarrow +\infty} \lambda_{1,k} = \lambda_1 > 0 \quad \text{and} \quad \lim_{k \rightarrow +\infty} Z_k = Z$$

in $W_{L\text{-per}}^{2,p}$ and $\mathcal{C}_{L\text{-per}}^{1,\gamma}$ for any $p < \infty$ and $\gamma < 1$.

Proof. In view of Lemma 3.9, $(Z_k)_k$ converges to some limit Z_∞ in $W_{L\text{-per}}^{2,p}$ and $\mathcal{C}^{1,\gamma}$ for any $p < \infty$ and $\gamma < 1$. This limit is obviously an eigenfunction associated with the eigenvalue $\liminf_{k \rightarrow +\infty} \lambda_{1,k}$ and, moreover, Z_∞ is L -periodic, $\max Z_\infty = 1$ and $Z_\infty > 0$. Hence, by uniqueness up to normalization of the positive eigenfunction, the result follows. \square

3.4. Uniqueness of solutions. We conclude with the following observation.

Lemma 3.11. *The solution in Lemma 3.6 is unique in \mathcal{O}_ε .*

Proof. By homotopy, the Leray–Schauder degree of $H(u_1, u_2; t)$ at 0 is constant for $t \in [0, 1]$. For $t = 0$, we know that

$$\deg_{X^2}(H(\cdot, \cdot; t), \mathcal{O}_\varepsilon, 0) = \text{index}_{X^2}(\mathcal{O}_\varepsilon; (u_1, u_2)) = 1.$$

On the other hand, by Lemma 3.10, any solution of the equation $H(u_1, u_2; 1) = 0$ in \mathcal{O}_ε is linearly stable, and thus also isolated. By conservation of the Leray–Schauder degree, it must be that the solution in \mathcal{O}_ε is unique. \square

APPENDIX A. A TECHNICAL ESTIMATE

Lemma A.1. *There exists a universal constant $C > 0$ such that for all $A > 0$, $B > 0$ and $k > 0$, if u satisfies*

$$\begin{cases} -u'' + k(1 - x^2)u \leq B & \text{in } (-1, 1) \\ 0 < u < A \end{cases}$$

then the following estimate holds

$$k(1 - x^2)u(x) \leq C \frac{A}{(1 - x^2)^2} + 2B.$$

We observe that, for x close to 0 (the point of minimum of the right hand side) the estimate is sharp, at least with respect to the order. Indeed the solution of the equation with $u(0) = B/(2k)$ and $u'(0) = 0$ is not positive in the interval $(-1, 1)$.

Proof. For any $x \in (-1, 1)$, let $d(x) = 1 - |x|$ be the distance of x to $\{-1, 1\}$. We observe that $d(x) < (1 - x^2) < 2d(x)$. We have, for $y \in (-1, 1)$, that

$$\begin{cases} -u'' + kd(y)u \leq B & \text{in } B_{d(y)}(y) \\ 0 < u < A. \end{cases}$$

By [22, Lemma 2.2], we have that there exists a universal constant $C > 0$ such that

$$kd(y)u(y) \leq \frac{CA}{d(y)^2} + B$$

and we can easily reach the conclusion. \square

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