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A TRULY TWO-DIMENSIONAL, ASYMPTOTIC-PRESERVING SCHEME FOR A DISCRETE MODEL OF RADIATIVE TRANSFER

LAURENT GOSSE* AND NICOLAS VAUCHELET†

Abstract. For a four-stream approximation of the kinetic model of radiative transfer with isotropic scattering, a numerical scheme endowed with both truly-2D well-balanced and diffusive asymptotic-preserving properties is derived, in the same spirit as what was done in [14] in the 1D case. Building on former results of Birkhoff and Abu-Shumays, [4], it is possible to express 2D kinetic steady-states by means of harmonic polynomials, and this allows to build a scattering S -matrix yielding a time-marching scheme. Such a S -matrix can be decomposed, as in [15], so as to deduce another scheme, well-suited for a diffusive approximation of the kinetic model, for which rigorous convergence can be proved. Challenging benchmarks are also displayed on coarse grids.

Key words. Diffusive scaling; Four-stream approximation; Grey radiative transfer; S -matrix.

AMS subject classifications. 31A05, 65M06, 76R50, 82B40, 85A25.

1. Introduction and preliminaries.

1.1. Kinetic modeling in 2D. We are interested in a “truly two-dimensional” numerical simulation of the simple kinetic model, where $\mathbf{x} = (x, y)$ and $\mathbf{v} = (\xi, \eta)$,

$$\partial_t f(t, \mathbf{x}, \mathbf{v}) + \mathbf{v} \cdot \nabla_{\mathbf{x}} f = \sigma(\mathbf{x}) \left(\int_{\mathbb{S}^1} f(t, \mathbf{x}, \mathbf{v}') \frac{d\mathbf{v}'}{2\pi} - f \right), \quad |\mathbf{v}| = 1.$$

in particular, of its “four-stream approximation”, evoked in *e.g.* [17, §5] or [9],

$$\partial_t f^\pm \pm \partial_x f^\pm = \sigma(x, y)(\rho/4 - f^\pm), \quad \partial_t g^\pm \pm \partial_y g^\pm = \sigma(x, y)(\rho/4 - g^\pm), \quad (1.1)$$

where the “opacity” $\sigma(x, y) \geq 0$ and the macroscopic density simplifies into,

$$\forall t, \mathbf{x} \in \mathbb{R}^+ \times \mathbb{R}^2, \quad \rho(t, \mathbf{x}) = f^+(t, \mathbf{x}) + f^-(t, \mathbf{x}) + g^+(t, \mathbf{x}) + g^-(t, \mathbf{x}).$$

In order to take full advantage of a 9-points, so-called *Moore*, stencil, microscopic velocities are rotated so as to be aligned with the diagonals of a Cartesian grid,

$$\mathbf{v} = \left(\frac{\pm 1}{\sqrt{2}}(1, 1), \frac{\pm 1}{\sqrt{2}}(-1, 1) \right), \quad (1.2)$$

like, for instance, in [5, §2.1]. This choice leads to the following 2D system,

$$\begin{cases} \partial_t f^\pm \pm \frac{1}{\sqrt{2}} (\partial_x f^\pm + \partial_y g^\pm) = \sigma(x, y) \left(\frac{\rho}{4} - f^\pm \right), \\ \partial_t g^\pm \mp \frac{1}{\sqrt{2}} (\partial_x f^\pm - \partial_y g^\pm) = \sigma(x, y) \left(\frac{\rho}{4} - g^\pm \right), \end{cases} \quad (1.3)$$

for which we propose a numerical scheme endowed with similar properties as the one in [14], in a two-dimensional context, without domain decomposition, like [2, 16, 19].

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1.2. Diffusive approximation to (1.1). To study diffusive limits of (1.1), one rescales $(t, \mathbf{x}) \rightarrow (\varepsilon^2 t, \varepsilon \mathbf{x})$ in order to produce,

$$\varepsilon \partial_t f^\pm \pm \partial_x f^\pm = \frac{\sigma(\mathbf{x})}{\varepsilon} \left(\frac{\rho}{4} - f^\pm \right), \quad \varepsilon \partial_t g^\pm \pm \partial_y g^\pm = \frac{\sigma(\mathbf{x})}{\varepsilon} \left(\frac{\rho}{4} - g^\pm \right),$$

and introduces macroscopic quantities, mass and flux,

$$\rho = f^+ + f^- + g^+ + g^-, \quad \mathbf{J} = \frac{1}{\varepsilon} \begin{pmatrix} f^+ - f^- \\ g^+ - g^- \end{pmatrix} \in \mathbb{R}^2.$$

By summing the four balance laws, the continuity equation emerges,

$$\partial_t \rho + \operatorname{div} \mathbf{J} = 0.$$

However, as noted in [17, page 504], the equation on \mathbf{J} isn't closed,

$$\varepsilon^2 \partial_t \mathbf{J} + \nabla \begin{pmatrix} f^+ + f^- \\ g^+ + g^- \end{pmatrix} = -\sigma(\mathbf{x}) \mathbf{J}, \quad (1.4)$$

so that, formally, the asymptotic behavior appears to be given by,

$$\partial_t \rho = \partial_x \left(\frac{\partial_x (f^+ + f^-)}{\sigma(\mathbf{x})} \right) + \partial_y \left(\frac{\partial_y (g^+ + g^-)}{\sigma(\mathbf{x})} \right).$$

However, by subtracting the first (second) and the third (fourth) balance laws,

$$\varepsilon \partial_t (f^\pm - g^\pm) \pm (\partial_x f^\pm - \partial_y g^\pm) = -\frac{\sigma}{\varepsilon} (f^\pm - g^\pm),$$

we get that $|f^\pm - g^\pm| = O(\varepsilon)$, so former calculations can be improved into,

$$\varepsilon^2 \partial_t \mathbf{J} + \nabla \left(\frac{\rho}{2} \right) = -\sigma \mathbf{J} - \frac{1}{2} \nabla \left(\begin{pmatrix} f^+ - g^+ \\ g^+ - f^+ \end{pmatrix} + \begin{pmatrix} f^- - g^- \\ g^- - f^- \end{pmatrix} \right) = -\sigma \mathbf{J} - O(\varepsilon),$$

which leads to the expected diffusion equation (see also (4.8)),

$$\partial_t \rho(t, \mathbf{x}) = \operatorname{div} \left(\frac{\nabla \rho}{2\sigma(\mathbf{x})} \right), \quad \text{or } \partial_t \rho = \frac{\Delta \rho}{2\sigma} \text{ if } \sigma \text{ is a constant.} \quad (1.5)$$

These formal arguments were made fully rigorous in [17] when σ is a constant.

1.3. Plan of the paper. This text follows a similar roadmap as the original article [14], with the supplementary difficulty that every derivation must now be made on two-dimensional kinetic models. To proceed, we recall in §2 the pioneering results of [4], thanks to which one can deduce, by means of Laplace transforms, kinetic steady-states from harmonic functions. Following ideas of [12, 13], a S -matrix is derived, in §3, from the data of such polynomial kinetic steady-states, yielding a time-marching scheme (3.5), which is able to preserve non-trivial 2D equilibria (see Theorem 3.2). Moreover, the S -matrix being doubly-stochastic, it is straightforward to show that (3.5) preserves positivity as well as L^1/L^∞ bounds, like its continuous counterpart. Drawing on our paper [15], after a parabolic rescaling of variables, the S -matrix decomposes nicely so as to yield an IMEX scheme (4.1) which relaxes, as $\varepsilon \rightarrow 0$, towards (4.8), which is a consistent discretization of (1.5). Rigorous proofs are produced in §5, in particular in Theorem 5.6, where we can see that the multi-dimensional feature (1.4), raised in [17], has consequences at the numerical level. These bounds are visualized in §6 where several challenging benchmarks for both (3.5) and (4.3) are tested on a coarse 32×32 Cartesian grid. Finally, §7 paves the way for tackling more complex kinetic models, like (7.1), and some early results of [14] are rephrased in the context of S -matrices in Appendix A.

2. Harmonic stationary distributions.

2.1. Harmonic functions and isotropic scattering. In [4], the authors present a tricky procedure which allows to derive an infinity of (explicit) exact steady-states of the following multi-dimensional kinetic model,

$$\partial_t f(t, \mathbf{x}, \mathbf{v}) + \mathbf{v} \cdot \nabla_{\mathbf{x}} f = \int_{\mathbb{S}^1} f(t, \mathbf{x}, \mathbf{v}') \frac{d\mathbf{v}'}{2\pi} - f, \quad \mathbf{x} = (x, y), \quad \mathbf{v} = (\xi, \eta).$$

In virtue of the method of characteristics, long-time asymptotics $t \rightarrow +\infty$ satisfy,

$$f(\mathbf{x}, \mathbf{v}) = \int_0^\infty \exp(-r) \rho(\mathbf{x} - r\mathbf{v}) dr, \quad \rho(\mathbf{x}) = \int_{\mathbb{S}^1} f(\mathbf{x}, \mathbf{v}) \frac{d\mathbf{v}}{2\pi}, \quad (2.1)$$

which is the Laplace transform of the (oriented) one-dimensional trace of ρ , [18],

$$\tilde{\rho}_{\mathbf{x}, \mathbf{v}} : \mathbb{R}^+ \ni r \mapsto \rho(\mathbf{x} - r\mathbf{v}), \quad f(\mathbf{x}, \mathbf{v}) = \mathcal{L}_r(\tilde{\rho}_{\mathbf{x}, \mathbf{v}})[p = 1]. \quad (2.2)$$

A Fredholm equation (of the second kind) follows by integrating again in $\mathbf{v} \in \mathbb{S}^1$,

$$\forall \mathbf{x} \in \mathbb{R}^2, \quad \rho(\mathbf{x}) = \int_0^\infty \exp(-r) \left(\int_{\mathbb{S}^1} \rho(\mathbf{x} - r\mathbf{v}) \frac{d\mathbf{v}}{2\pi} \right) dr. \quad (2.3)$$

At this point, the authors of [4] claim that, as the long-time behavior of the kinetic model is pure diffusion and ρ is a macroscopic quantity, *harmonic functions may induce mesoscopic steady-states by means of (2.1)*. Hence, if ρ is a steady-state of diffusion, $\Delta\rho = 0$, and its mean-value property [6, 10, 20] yields,

$$\forall r \in \mathbb{R}^+, \quad \rho(\mathbf{x}) = \int_{\mathbb{S}^1} \rho(\mathbf{x} - r\mathbf{v}) \frac{d\mathbf{v}}{2\pi},$$

so that, by multiplying by $\exp(-r)$ and integrating in $r \in \mathbb{R}^+$,

$$\int_0^\infty \rho(\mathbf{x}) \exp(-r) dr = \rho(\mathbf{x}) = \int_0^\infty \exp(-r) \left(\int_{\mathbb{S}^1} \rho(\mathbf{x} - r\mathbf{v}) \frac{d\mathbf{v}}{2\pi} \right) dr,$$

holds for any $\mathbf{x} \in \mathbb{R}^2$, so that (2.3) is satisfied, and a class of stationary kinetic densities $f(\mathbf{x}, \mathbf{v})$ can be deduced from (2.1). For instance, harmonic polynomials furnish an infinity of 2D mesoscopic steady-states, which generalize the only two $1, x - v$ (see *e.g.* [11, Chap. 9]), which follow from $\rho''(x) = 0$ in one dimension.

2.2. Kinetic steady-states and harmonic polynomials. A major result in [4] is that *kinetic stationary solutions $f(\mathbf{x}, \mathbf{v})$ can be deduced from macroscopic (i.e. diffusive, or harmonic) ones $\rho(\mathbf{x})$* , by means of a Laplace transform of $r \mapsto \rho(\mathbf{x} - r\mathbf{v})$,

$$f(\mathbf{x}, \mathbf{v}) = \int_0^\infty \rho(\mathbf{x} - r\mathbf{v}) \exp(-r) dr, \quad \Delta\rho = 0, \quad (2.4)$$

as soon as certain integrability conditions are met (see [4, Theorem A]). Accordingly, in the special case where $\mathbf{x} = x \in \mathbb{R}$ (one space dimension), harmonic solutions of $d^2\rho/dx^2 = 0$ reduce to $\{1, x\}$ and it comes that, for $v \in \mathbb{R}$,

$$f(x, v) = \int_0^\infty \exp(-r) dr = 1, \quad f(x, v) = \int_0^\infty (x - rv) \exp(-r) dr = x - v,$$

which are well-known “separated variables Case’s solutions”, see [11, eqn (9.8)]. In more space dimensions, harmonic functions are abundant (any holomorphic function of $z = x + iy \in \mathbb{C}$ furnishes two harmonic ones: its real and imaginary parts), so that (2.4) yields an infinite set of polynomial solutions, being

$$f(\mathbf{x}, \mathbf{v}) = \left\{ 1, \mathbf{x} - \mathbf{v} \in \mathbb{R}^2, \right. \\ \left. xy - (x\eta + y\xi) + 2\xi\eta, \frac{x^2 - y^2}{2} - (x\xi - y\eta) + (\xi^2 - \eta^2), \dots \text{etc} \right\}, \quad (2.5)$$

see [4, eqn (2.6)]. The first ones correspond to “dimensional splitting”, whereas last two ones are truly 2D and “conjugate” in a certain sense (as seen below). These stationary distributions $f(\mathbf{x}, \mathbf{v})$ can be easily retrieved from (2.4) by taking advantage of the expression of harmonic functions in polar coordinates,

$$\rho(x = r \cos \theta, y = r \sin \theta) = a_0 + \sum_{n \in \mathbb{N}_*} (a_n \cos n\theta + b_n \sin n\theta) r^n, \quad (2.6)$$

in which the first basis components are

$$\left\{ 1, x = r \cos \theta, y = r \sin \theta, x^2 - y^2 = r^2 \cos 2\theta, xy = r^2 \sin 2\theta, \dots \right\}.$$

These “harmonic steady-states” $f(\mathbf{x}, \mathbf{v})$ follow from Euler’s Gamma function,

$$\Gamma(x) = \int_0^\infty \exp(-t) t^{x-1} dt, \quad \Gamma(n) = (n-1)! \text{ if } n \in \mathbb{N},$$

because, according to (2.1), the polynomial solutions given in (2.6) rewrite,

$$f(\mathbf{x}, \mathbf{v}) = \left\{ \Gamma(1), \Gamma(1)\mathbf{x} - \Gamma(2)\mathbf{v}, \Gamma(1)xy - \Gamma(2)(x\eta + y\xi) + \Gamma(3)\xi\eta, \dots \right\}.$$

3. A “truly 2D” approximation of $f(t, \mathbf{x}, \mathbf{v})$. Working on a uniform Cartesian grid for which $\Delta x = \Delta y$, we mimic the notation already used in [3], see Fig. 3.1.

3.1. Derivation of the S -matrix. In order to simulate (1.3) on a 9-points stencil, we only need the first four stationary solutions: the choice between the two “truly 2D” quadratic ones depends on the velocity vectors. A simple case, where one of the conjugate solutions is always null, consists in working in diagonal coordinates,

$$\mathbf{x} = (\mp R, 0) \text{ and } (0, \mp R), \quad \mathbf{v} = (\pm 1, 0) \text{ and } (0, \pm 1),$$

where $R = \Delta x / \sqrt{2}$ is the radius of the disc centered in $x_{i-\frac{1}{2}}, y_{j+\frac{1}{2}}$. The S -matrix acts on four incoming states and produces four outgoing ones, so

$$\begin{pmatrix} f_*^+ \\ f_*^- \\ g_*^+ \\ g_*^- \end{pmatrix} = S_{i-\frac{1}{2}, j+\frac{1}{2}} \begin{pmatrix} f_{i-1, j}^+ \\ f_{i, j+1}^- \\ g_{i, j}^+ \\ g_{i-1, j+1}^- \end{pmatrix}.$$

By linearity, and following ideas from [11, Chap. 9], a C^∞ stationary solution reads,

$$f(\mathbf{x}, \mathbf{v}) = \alpha + \beta(x - \xi) + \gamma(y - \eta) + \nu \left(\frac{x^2 - y^2}{2} - (x\xi - y\eta) + (\xi^2 - \eta^2) \right), \quad (3.1)$$

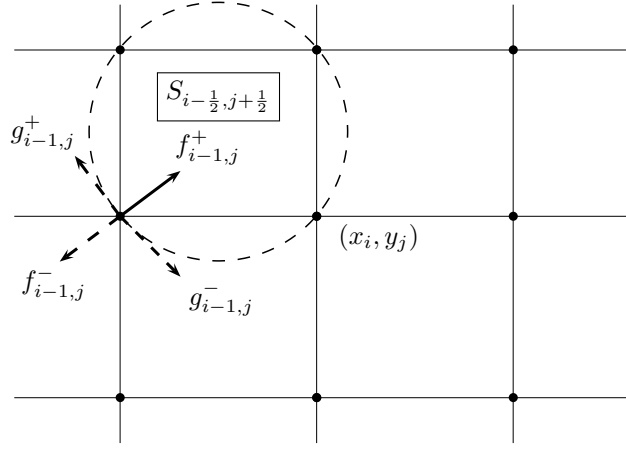


FIGURE 3.1. The S -matrix $S_{i-\frac{1}{2}, j+\frac{1}{2}}$ and an incoming state, $f_{i-1, j}^+$.

so that aforementioned “incoming” and “outgoing” states are, respectively,

$$\begin{cases} f_{i-1, j}^+ = f(\mathbf{x} = (-R, 0), \mathbf{v} = (1, 0)), & f_{i, j+1}^- = f(\mathbf{x} = (R, 0), \mathbf{v} = (-1, 0)), \\ g_{i, j}^+ = f(\mathbf{x} = (0, -R), \mathbf{v} = (0, 1)), & g_{i-1, j+1}^- = f(\mathbf{x} = (0, R), \mathbf{v} = (0, -1)), \end{cases}$$

which is a linear system for $(\alpha, \beta, \gamma, \nu)$, and

$$\begin{cases} f_*^+ = f(\mathbf{x} = (R, 0), \mathbf{v} = (1, 0)), & f_*^- = f(\mathbf{x} = (-R, 0), \mathbf{v} = (-1, 0)), \\ g_*^+ = f(\mathbf{x} = (0, R), \mathbf{v} = (0, 1)), & g_*^- = f(\mathbf{x} = (0, -R), \mathbf{v} = (0, -1)), \end{cases}$$

involving again the “spectral coefficients” $(\alpha, \beta, \gamma, \nu) \in \mathbb{R}^4$ which values are fixed by the four incoming states. Accordingly, the S -matrix decomposes again like,

$$\forall (i, j) \in \mathbb{Z}^2, \quad S_{i-\frac{1}{2}, j+\frac{1}{2}} = S(\sigma_{i-\frac{1}{2}, j+\frac{1}{2}}), \quad S(\sigma) = \tilde{M} M^{-1}, \quad (3.2)$$

where M has mutually orthogonal columns,

$$M = \begin{pmatrix} 1 & -(1 + \sigma R) & 0 & 1 + (1 + \sigma R)^2 \\ 1 & (1 + \sigma R) & 0 & 1 + (1 + \sigma R)^2 \\ 1 & 0 & -(1 + \sigma R) & -(1 + (1 + \sigma R)^2) \\ 1 & 0 & (1 + \sigma R) & -(1 + (1 + \sigma R)^2) \end{pmatrix}, \quad (3.3)$$

along with its companion \tilde{M} ,

$$\tilde{M} = \begin{pmatrix} 1 & -(1 - \sigma R) & 0 & 1 + (1 - \sigma R)^2 \\ 1 & 1 - \sigma R & 0 & 1 + (1 - \sigma R)^2 \\ 1 & 0 & -(1 - \sigma R) & -(1 + (1 - \sigma R)^2) \\ 1 & 0 & (1 - \sigma R) & -(1 + (1 - \sigma R)^2) \end{pmatrix},$$

in which a rescaling of \mathbf{x} was made in order to cope with variable opacity $\sigma(\mathbf{x})$. One recognizes the matrices of 1D Goldstein-Taylor model, see §A and [11, Remark 9.3],

$$\begin{pmatrix} 1 & -(1 + \sigma R) \\ 1 & (1 + \sigma R) \end{pmatrix}, \quad \begin{pmatrix} 1 & -(1 - \sigma R) \\ 1 & (1 - \sigma R) \end{pmatrix},$$

but now, 1D solutions $\sigma \mathbf{x} - \mathbf{v}$ are coupled by the constant and quadratic ones.

3.2. Resulting 2D time-marching scheme. For $\sigma R \geq 0$, the determinant $|M|$ is positive, so M is invertible and its inverse reads:

$$|M| = 8(1 + \sigma R)^2 (1 + (1 + \sigma R)^2), \quad M^{-1} = \begin{pmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ -A & A & 0 & 0 \\ 0 & 0 & -A & A \\ B & B & -B & -B \end{pmatrix},$$

so that α is always the average of the four incoming states, and where

$$A = \frac{1}{2(1 + \sigma R)}, \quad B = \frac{1}{4(1 + (1 + \sigma R)^2)}.$$

Accordingly, the S -matrix is given by the product,

$$\begin{aligned} S(\sigma) &= \tilde{M} M^{-1} \\ &= \begin{pmatrix} \frac{1}{4} + C + D & \frac{1}{4} - C + D & \frac{1}{4} - D & \frac{1}{4} - D \\ \frac{1}{4} - C + D & \frac{1}{4} + C + D & \frac{1}{4} - D & \frac{1}{4} - D \\ \frac{1}{4} - D & \frac{1}{4} - D & \frac{1}{4} + C + D & \frac{1}{4} - C + D \\ \frac{1}{4} - D & \frac{1}{4} - D & \frac{1}{4} - C + D & \frac{1}{4} + C + D \end{pmatrix}, \end{aligned} \quad (3.4)$$

which both lines and columns clearly add to unity, because

$$C = \frac{1 - \sigma R}{2(1 + \sigma R)} = \frac{1}{2} - \frac{\sigma R}{1 + \sigma R}, \quad D = \frac{(1 - \sigma R)^2 + 1}{4((1 + \sigma R)^2 + 1)} = \frac{1}{4} - \frac{\sigma R}{1 + (1 + \sigma R)^2}.$$

The S -matrix rewrites as a $O(\sigma R)$ -perturbation of the identity of \mathbb{R}^4 ,

$$\begin{aligned} S(\sigma) &= \text{Id}_{\mathbb{R}^4} + \sigma R \left\{ \frac{1}{1 + \sigma R} \begin{pmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{pmatrix} \right. \\ &\quad \left. + \frac{1}{1 + (1 + \sigma R)^2} \begin{pmatrix} -1 & -1 & 1 & 1 \\ -1 & -1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & 1 & -1 & -1 \end{pmatrix} \right\}, \end{aligned}$$

so that, similarly to *e.g.* [15, Prop. 3.2],

$$S(\sigma) \rightarrow \text{Id}_{\mathbb{R}^4} \text{ if } \sigma \rightarrow 0, \quad S(\sigma) \rightarrow S^0 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \text{ if } \sigma \rightarrow +\infty.$$

Having at hand the 4×4 matrix (3.2) allows to deduce a time-marching scheme for the 2D system (1.3) on a uniform Cartesian grid (see Fig. 3.1, $\Delta x = \Delta y$),

$$\begin{pmatrix} f_{i,j+1}^{+,n+1} \\ f_{i,j+1}^{-,n+1} \\ f_{i-1,j}^{+,n+1} \\ g_{i-1,j+1}^{-,n+1} \\ g_{i,j}^{-,n+1} \end{pmatrix} = \left(1 - \frac{\Delta t}{2R}\right) \begin{pmatrix} f_{i,j+1}^{+,n} \\ f_{i-1,j}^{-,n} \\ g_{i-1,j+1}^{+,n} \\ g_{i,j}^{-,n} \end{pmatrix} + \frac{\Delta t}{2R} S(\sigma_{i-\frac{1}{2},j+\frac{1}{2}}) \begin{pmatrix} f_{i-1,j}^{+,n} \\ f_{i,j+1}^{-,n} \\ g_{i,j}^{+,n} \\ g_{i-1,j+1}^{-,n} \end{pmatrix}. \quad (3.5)$$

LEMMA 3.1. *Under the CFL restriction $\Delta t \leq 2R$, the scheme (3.5) is consistent with (1.3) and preserves positivity. Moreover, it is conservative and L^∞ -bounded.*

Proof. Under the aforementioned CFL restriction, (3.5) is a convex combination (as advocated in [12, eqn (2.2)]), hence it preserves positivity because all the entries of $S(\sigma)$ are nonnegative. Besides, doubly-stochastic matrices are such that,

$$\forall \vec{v} \in \mathbb{R}^4, \quad \|S(\sigma)\vec{v}\|_\infty \leq \|\vec{v}\|_\infty, \quad \|S(\sigma)\vec{v}\|_1 \leq \|\vec{v}\|_1,$$

which implies that (3.5) is bounded in L^1 and L^∞ . Consistency is shown for $0 \leq \sigma R \ll 1$ (fine grid); at first order, the expression of the S -matrix reduces to,

$$\frac{1}{1 + (1 + \sigma R)^2} \simeq \frac{1}{2(1 + \sigma R)}, \quad S(\sigma) = \text{Id}_{\mathbb{R}^4} + \frac{\sigma R}{2(1 + \sigma R)} \begin{pmatrix} -3 & 1 & 1 & 1 \\ 1 & -3 & 1 & 1 \\ 1 & 1 & -3 & 1 \\ 1 & 1 & 1 & -3 \end{pmatrix},$$

and inserting this expression in (3.5) yields a consistent approximation of (1.3). \square

The scheme (3.5) is able to preserve some non-trivial 2D equilibria, see *e.g.* [1].

THEOREM 3.2 (2D well-balanced). *Let $\sigma(\mathbf{x}) \equiv \bar{\sigma} > 0$ a constant, then any linear combination (3.1) induces a numerical steady-state for the scheme (3.5), given by*

$$f^\pm \left(\frac{x-y}{\sqrt{2}}, \frac{x+y}{\sqrt{2}} \right) = f(\bar{\sigma}\mathbf{x}; (\pm 1, 0)), \quad g^\pm \left(\frac{x-y}{\sqrt{2}}, \frac{x+y}{\sqrt{2}} \right) = f(\bar{\sigma}\mathbf{x}; (0, \pm 1)).$$

Proof. Pick $(\alpha, \beta, \gamma, \nu) \in \mathbb{R}^4$ in (3.1) and consider a steady-state $f(\bar{\sigma}\mathbf{x}, \mathbf{v})$: since $|M| > 0$, its restriction to $\mathbf{v} = \{(\pm 1, 0), (0, \pm 1)\}$ on a uniform Cartesian grid satisfies,

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \nu \end{pmatrix} = M^{-1} \begin{pmatrix} f_{i-1,j}^{+,n} \\ f_{i,j+1}^{-,n} \\ g_{i,j}^{+,n} \\ g_{i-1,j+1}^{-,n} \end{pmatrix} \Rightarrow S(\bar{\sigma}) \begin{pmatrix} f_{i-1,j}^{+,n} \\ f_{i,j+1}^{-,n} \\ g_{i,j}^{+,n} \\ g_{i-1,j+1}^{-,n} \end{pmatrix} = \begin{pmatrix} f_{i,j+1}^{+,n} \\ f_{i-1,j}^{-,n} \\ g_{i-1,j+1}^{+,n} \\ g_{i,j}^{-,n} \end{pmatrix},$$

so they are invariant by the time-marching scheme (3.5). By a $-\frac{\pi}{4}$ rotation we pass from diagonal coordinates with $\mathbf{v} = \{(\pm 1, 0), (0, \pm 1)\}$ to axial ones with (1.2). \square

4. Diffusive behavior of the S -matrix. In order to study asymptotic limits so as to check a possible consistency with the estimates stated in [17, Theorem 5.1], we rescale $\sigma(\mathbf{x}) \rightarrow \sigma(\mathbf{x})/\varepsilon$, $\varepsilon \ll 1$. Accordingly, the S -matrix decomposes into $S^0 + \varepsilon S^{1,\varepsilon}$, like in [15, §1.2], where, as $\varepsilon \rightarrow 0$, Following again [15], an IMEX scheme may read

$$\begin{aligned} & \begin{pmatrix} f_{i,j+1}^{+,n+1} \\ f_{i,j+1}^{-,n+1} \\ f_{i-1,j}^{+,n+1} \\ g_{i-1,j+1}^{+,n+1} \\ g_{i,j}^{-,n+1} \end{pmatrix} + \frac{\Delta t}{2\varepsilon R} \left\{ \begin{pmatrix} f_{i,j+1}^{+,n+1} \\ f_{i-1,j}^{-,n+1} \\ g_{i-1,j+1}^{+,n+1} \\ g_{i,j}^{-,n+1} \end{pmatrix} - S^0 \begin{pmatrix} f_{i-1,j}^{+,n+1} \\ f_{i,j+1}^{-,n+1} \\ g_{i,j}^{+,n+1} \\ g_{i-1,j+1}^{-,n+1} \end{pmatrix} \right\} \\ & = \begin{pmatrix} f_{i,j+1}^{+,n} \\ f_{i-1,j}^{-,n} \\ g_{i-1,j+1}^{+,n} \\ g_{i,j}^{-,n} \end{pmatrix} + \frac{\Delta t}{2R} S^{1,\varepsilon} \begin{pmatrix} f_{i-1,j}^{+,n} \\ f_{i,j+1}^{-,n} \\ g_{i,j}^{+,n} \\ g_{i-1,j+1}^{-,n} \end{pmatrix}, \end{aligned} \quad (4.1)$$

and we expect the (implicit, but not costly) left-hand side to yield ‘‘Maxwellian estimates’’ of the type [17, eqn (5.15)], and the (explicit) right-hand side to produce accurate and consistent diffusive numerical fluxes.

4.1. Decomposition of the S -matrix. By defining the positive coefficients,

$$\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon = \frac{1}{\varepsilon + \sigma_{i-\frac{1}{2},j+\frac{1}{2}} R}; \quad \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon = \frac{\sigma_{i-\frac{1}{2},j+\frac{1}{2}} R}{\varepsilon^2 + (\varepsilon + \sigma_{i-\frac{1}{2},j+\frac{1}{2}} R)^2}, \quad (4.2)$$

the aforementioned decomposition reads, at each location $i - \frac{1}{2}, j + \frac{1}{2}$,

$$S^\varepsilon = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} + \varepsilon \begin{pmatrix} \alpha - \beta & -(\alpha + \beta) & \beta & \beta \\ -(\alpha + \beta) & \alpha - \beta & \beta & \beta \\ \beta & \beta & \alpha - \beta & -(\alpha + \beta) \\ \beta & \beta & -(\alpha + \beta) & \alpha - \beta \end{pmatrix},$$

hence, the IMEX scheme (4.1) rewrites as,

$$\begin{aligned} f_{i,j+1}^{+,n+1} + \frac{\Delta t}{2\varepsilon R} (f_{i,j+1}^{+,n+1} - f_{i,j+1}^{-,n+1}) &= f_{i,j+1}^{+,n} + \\ &\frac{\Delta t}{2R} \left[\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i-1,j}^{+,n} - f_{i,j+1}^{-,n}) + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (-f_{i-1,j}^{+,n} - f_{i,j+1}^{-,n} + g_{i,j}^{+,n} + g_{i-1,j+1}^{-,n}) \right] \\ f_{i-1,j}^{-,n+1} + \frac{\Delta t}{2\varepsilon R} (f_{i-1,j}^{-,n+1} - f_{i-1,j}^{+,n+1}) &= f_{i-1,j}^{-,n} + \\ &\frac{\Delta t}{2R} \left[\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i,j+1}^{-,n} - f_{i-1,j}^{+,n}) + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (-f_{i-1,j}^{+,n} - f_{i,j+1}^{-,n} + g_{i,j}^{+,n} + g_{i-1,j+1}^{-,n}) \right] \\ g_{i-1,j+1}^{+,n+1} + \frac{\Delta t}{2\varepsilon R} (g_{i-1,j+1}^{+,n+1} - g_{i-1,j+1}^{-,n+1}) &= g_{i-1,j+1}^{+,n} + \\ &\frac{\Delta t}{2R} \left[\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (g_{i,j}^{+,n} - g_{i-1,j+1}^{-,n}) + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i-1,j}^{+,n} + f_{i,j+1}^{-,n} - g_{i,j}^{+,n} - g_{i-1,j+1}^{-,n}) \right] \\ g_{i,j}^{-,n+1} + \frac{\Delta t}{2\varepsilon R} (g_{i,j}^{-,n+1} - g_{i,j}^{+,n+1}) &= g_{i,j}^{-,n} + \\ &\frac{\Delta t}{2R} \left[\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (g_{i-1,j+1}^{-,n} - g_{i,j}^{+,n}) + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i-1,j}^{+,n} + f_{i,j+1}^{-,n} - g_{i,j}^{+,n} - g_{i-1,j+1}^{-,n}) \right]. \end{aligned}$$

An index-shift yields:

$$\begin{pmatrix} 1 + \frac{\Delta t}{2\varepsilon R} & -\frac{\Delta t}{2\varepsilon R} & 0 & 0 \\ -\frac{\Delta t}{2\varepsilon R} & 1 + \frac{\Delta t}{2\varepsilon R} & 0 & 0 \\ 0 & 0 & 1 + \frac{\Delta t}{2\varepsilon R} & -\frac{\Delta t}{2\varepsilon R} \\ 0 & 0 & -\frac{\Delta t}{2\varepsilon R} & 1 + \frac{\Delta t}{2\varepsilon R} \end{pmatrix} \begin{pmatrix} f_{i,j}^{+,n+1} \\ f_{i,j}^{-,n+1} \\ g_{i,j}^{+,n+1} \\ g_{i,j}^{-,n+1} \end{pmatrix} = \begin{pmatrix} f_{i,j}^{+,n} \\ f_{i,j}^{-,n} \\ g_{i,j}^{+,n} \\ g_{i,j}^{-,n} \end{pmatrix} + \quad (4.3)$$

$$\frac{\Delta t}{2R} \begin{pmatrix} \alpha_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon (f_{i-1,j-1}^{+,n} - f_{i,j}^{-,n}) - \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon (f_{i-1,j-1}^{+,n} + f_{i,j}^{-,n} - g_{i,j-1}^{+,n} - g_{i-1,j}^{-,n}) \\ \alpha_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i+1,j+1}^{-,n} - f_{i,j}^{+,n}) - \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i,j}^{+,n} + f_{i+1,j+1}^{-,n} - g_{i+1,j}^{+,n} - g_{i,j+1}^{-,n}) \\ \alpha_{i+\frac{1}{2},j-\frac{1}{2}}^\varepsilon (g_{i+1,j-1}^{+,n} - g_{i,j}^{-,n}) + \beta_{i+\frac{1}{2},j-\frac{1}{2}}^\varepsilon (f_{i,j-1}^{+,n} + f_{i+1,j}^{-,n} - g_{i+1,j-1}^{+,n} - g_{i,j}^{-,n}) \\ \alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (g_{i-1,j+1}^{-,n} - g_{i,j}^{+,n}) + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i-1,j}^{+,n} + f_{i,j+1}^{-,n} - g_{i,j}^{+,n} - g_{i-1,j+1}^{-,n}) \end{pmatrix}.$$

The implicit part relies on a block-diagonal matrix, for which,

$$\begin{pmatrix} 1+b & -b \\ -b & 1+b \end{pmatrix}^{-1} = \frac{1}{a+b} \begin{pmatrix} a & b \\ b & a \end{pmatrix}, \quad b = \frac{\Delta t}{2\varepsilon R}, \quad a = 1 + \frac{\Delta t}{2\varepsilon R},$$

so that (4.3) rewrites as an explicit time-marching scheme. The matrix in the left hand side of (4.3) may be written as

$$\text{Id}_{\mathbb{R}^4} + \frac{\Delta t}{2\varepsilon R} H_0, \quad \text{with} \quad H_0 = \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & -1 & 1 \end{pmatrix}. \quad (4.4)$$

Denoting $\mathfrak{f}_{i,j}^n = f_{i,j}^{+,n} + f_{i,j}^{-,n}$ and $\mathfrak{g}_{i,j}^n = g_{i,j}^{+,n} + g_{i,j}^{-,n}$, their time evolution follows from adding the first two and the last two equations in (4.3):

$$\begin{aligned} \mathfrak{f}_{i,j}^{n+1} = \mathfrak{f}_{i,j}^n + \frac{\Delta t}{2R} & \left(\alpha_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon (f_{i-1,j-1}^{+,n} - f_{i,j}^{-,n}) + \alpha_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i+1,j+1}^{-,n} - f_{i,j}^{+,n}) \right) \\ & - \frac{\Delta t}{2R} \left(\beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon (f_{i-1,j-1}^{+,n} + f_{i,j}^{-,n} - g_{i,j-1}^{+,n} - g_{i-1,j}^{-,n}) \right. \\ & \left. + \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i,j}^{+,n} + f_{i+1,j+1}^{-,n} - g_{i+1,j}^{+,n} - g_{i,j+1}^{-,n}) \right) \end{aligned} \quad (4.5)$$

$$\begin{aligned} \mathfrak{g}_{i,j}^{n+1} = \mathfrak{g}_{i,j}^n + \frac{\Delta t}{2R} & \left(\alpha_{i+\frac{1}{2},j-\frac{1}{2}}^\varepsilon (g_{i+1,j-1}^{+,n} - g_{i,j}^{-,n}) + \alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (g_{i-1,j+1}^{-,n} - g_{i,j}^{+,n}) \right) \\ & + \frac{\Delta t}{2R} \left(\beta_{i+\frac{1}{2},j-\frac{1}{2}}^\varepsilon (f_{i,j-1}^{+,n} + f_{i+1,j}^{-,n} - g_{i+1,j-1}^{+,n} - g_{i,j}^{-,n}) \right. \\ & \left. + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon (f_{i-1,j}^{+,n} + f_{i,j+1}^{-,n} - g_{i,j}^{+,n} - g_{i-1,j+1}^{-,n}) \right). \end{aligned} \quad (4.6)$$

4.2. Formal diffusive limit. When $\varepsilon \rightarrow 0$, we deduce from (4.3) that,

$$\begin{pmatrix} f_{i,j}^{+,n+1} \\ f_{i,j}^{-,n+1} \\ g_{i,j}^{+,n+1} \\ g_{i,j}^{-,n+1} \end{pmatrix} \in \text{Ker}(H_0) = \text{Span} \left\{ \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 1 \\ 1 \end{pmatrix} \right\}. \quad (4.7)$$

Then, in the limit $\varepsilon \rightarrow 0$, we expect, at least formally, that

$$f_{i,j}^{+,n+1} = f_{i,j}^{-,n+1} = \frac{1}{2} \mathfrak{f}_{i,j}^{n+1}, \quad g_{i,j}^{+,n+1} = g_{i,j}^{-,n+1} = \frac{1}{2} \mathfrak{g}_{i,j}^{n+1},$$

along with, from (4.2),

$$\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon, \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon \rightarrow \frac{1}{\sigma_{i-\frac{1}{2},j+\frac{1}{2}} R}, \quad \varepsilon \rightarrow 0,$$

so that, former equations (4.5) and (4.6) become

$$\begin{aligned} \mathfrak{f}_{i,j}^{n+1} = \mathfrak{f}_{i,j}^n + \frac{\Delta t}{4R^2} & \left(\frac{1}{\sigma_{i-\frac{1}{2},j-\frac{1}{2}}} \left((\mathfrak{g}_{i-1,j}^n - \mathfrak{f}_{i,j}^n) + (\mathfrak{g}_{i,j-1}^n - \mathfrak{f}_{i,j}^n) \right) \right. \\ & \left. + \frac{1}{\sigma_{i+\frac{1}{2},j+\frac{1}{2}}} \left((\mathfrak{g}_{i+1,j}^n - \mathfrak{f}_{i,j}^n) + (\mathfrak{g}_{i,j+1}^n - \mathfrak{f}_{i,j}^n) \right) \right) \\ \mathfrak{g}_{i,j}^{n+1} = \mathfrak{g}_{i,j}^n + \frac{\Delta t}{4R^2} & \left(\frac{1}{\sigma_{i-\frac{1}{2},j+\frac{1}{2}}} \left((\mathfrak{f}_{i,j+1}^n - \mathfrak{g}_{i,j}^n) + (\mathfrak{f}_{i-1,j}^n - \mathfrak{g}_{i,j}^n) \right) \right. \\ & \left. + \frac{1}{\sigma_{i+\frac{1}{2},j-\frac{1}{2}}} \left((\mathfrak{f}_{i+1,j}^n - \mathfrak{g}_{i,j}^n) + (\mathfrak{f}_{i,j-1}^n - \mathfrak{g}_{i,j}^n) \right) \right). \end{aligned}$$

Accordingly, \mathfrak{f} and \mathfrak{g} satisfy similar diffusion equations, if the opacity σ is smooth. Consequently, if initially they are close enough (so-called “*well-prepared initial data*”), they can be expected to stay so because their difference $\mathfrak{f}_{i,j}^n - \mathfrak{g}_{i,j}^n$ satisfies a parabolic equation. The decay of $\mathfrak{f} - \mathfrak{g}$ will be rigorously proved when σ is a constant, see

Theorem 5.6. Adding, assuming $\mathbf{f} - \mathbf{g} \rightarrow 0$, and denoting $\rho_{i,j}^n = \mathbf{f}_{i,j}^n + \mathbf{g}_{i,j}^n$, it comes

$$\begin{aligned} \rho_{i,j}^{n+1} = \rho_{i,j}^n + \frac{\Delta t}{2\sigma R^2} & \left(\left(\frac{1}{2\sigma_{i+\frac{1}{2},j+\frac{1}{2}}} + \frac{1}{2\sigma_{i+\frac{1}{2},j-\frac{1}{2}}} \right) (\rho_{i+1,j}^n - \rho_{i,j}^n) \right. \\ & + \left(\frac{1}{2\sigma_{i+\frac{1}{2},j+\frac{1}{2}}} + \frac{1}{2\sigma_{i-\frac{1}{2},j+\frac{1}{2}}} \right) (\rho_{i,j+1}^n - \rho_{i,j}^n) \\ & - \left(\frac{1}{2\sigma_{i-\frac{1}{2},j+\frac{1}{2}}} + \frac{1}{2\sigma_{i-\frac{1}{2},j-\frac{1}{2}}} \right) (\rho_{i,j}^n - \rho_{i-1,j}^n) \\ & \left. - \left(\frac{1}{2\sigma_{i+\frac{1}{2},j-\frac{1}{2}}} + \frac{1}{2\sigma_{i-\frac{1}{2},j-\frac{1}{2}}} \right) (\rho_{i,j}^n - \rho_{i,j-1}^n) \right). \end{aligned} \quad (4.8)$$

which is a second-order, finite-differences, monotone (under the CFL restriction (5.6)) discretization of the macroscopic diffusion equation (1.5).

5. Rigorous uniform estimates for constant opacity. Let $(u_{i,j})$ stand for any real sequence, we introduce the following notations,

$$\begin{aligned} \delta u_{i+\frac{1}{2},j} &= u_{i+1,j} - u_{i,j}, \quad \delta u_{i,j+\frac{1}{2}} = u_{i,j+1} - u_{i,j}, \\ \|u\|_1 &= \sum_{i,j} \Delta x^2 |u_{i,j}|, \quad TV(u) = \sum_{i,j} \Delta x (|\delta u_{i+\frac{1}{2},j}| + |\delta u_{i,j+\frac{1}{2}}|), \\ \|\Delta u\|_1 &= \sum_{i,j} |u_{i+1,j} + u_{i,j+1} + u_{i-1,j} + u_{i,j-1} - 4u_{i,j}|. \end{aligned} \quad (5.1)$$

5.1. General properties of the scheme. The first stepping stone is the definition of a convenient CFL restriction:

LEMMA 5.1. *Assume that there exists $\sigma_{min} > 0$ such that the opacity is such that $0 < \sigma_{min} \leq \sigma_{i-\frac{1}{2},j+\frac{1}{2}}$ for all i, j . Then, under the CFL condition*

$$\Delta t \leq \min \left\{ \frac{2}{3} \sigma_{min} R^2, \frac{R(\varepsilon + \sigma_{min} R)}{2} \left(1 + \sqrt{1 + \frac{8\varepsilon}{\varepsilon + \sigma_{min} R}} \right) \right\}, \quad (5.2)$$

the IMEX scheme (4.3) preserves positivity.

Proof. Inverting the block-diagonal matrix in (4.3) brings the expressions,

$$\begin{aligned} f_{i,j}^{+,n+1} &= \frac{1}{2\varepsilon R + 2\Delta t} \left((2\varepsilon R + \Delta t - \frac{\Delta t^2}{2R} (\alpha_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon + \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon)) f_{i,j}^{+,n} \right. \\ &+ \left(\Delta t - \frac{\Delta t}{2R} (2\varepsilon R + \Delta t) (\alpha_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon + \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon) \right) f_{i,j}^{-,n} \\ &+ (2\varepsilon R + \Delta t) \frac{\Delta t}{2R} (\alpha_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon - \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon) f_{i-1,j-1}^{+,n} \\ &+ \frac{\Delta t^2}{2R} (\alpha_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon - \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon) f_{i+1,j+1}^{-,n} \\ &+ (2\varepsilon R + \Delta t) \frac{\Delta t}{2R} \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon (g_{i,j-1}^{+,n} + g_{i-1,j}^{-,n}) \\ &\left. + \frac{\Delta t^2}{2R} \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon (g_{i+1,j}^{+,n} + g_{i,j+1}^{-,n}) \right), \end{aligned} \quad (5.3)$$

and

$$\begin{aligned}
f_{i,j}^{-,n+1} &= \frac{1}{2\varepsilon R + 2\Delta t} \left((\Delta t - (2\varepsilon R + \Delta t)) \frac{\Delta t}{2R} (\alpha_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon + \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon) f_{i,j}^{+,n} \right. \\
&\quad + (2\varepsilon R + \Delta t - \frac{\Delta t^2}{2R} (\alpha_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon + \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon)) f_{i,j}^{-,n} \\
&\quad + \frac{\Delta t^2}{2R} (\alpha_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon - \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon) f_{i-1,j-1}^{+,n} \\
&\quad + (2\varepsilon R + \Delta t) \frac{\Delta t}{2R} (\alpha_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon - \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon) f_{i+1,j+1}^{-,n} \\
&\quad + \frac{\Delta t^2}{2R} \beta_{i-\frac{1}{2},j-\frac{1}{2}}^\varepsilon (g_{i,j-1}^{+,n} + g_{i-1,j}^{-,n}) \\
&\quad \left. + (2\varepsilon R + \Delta t) \frac{\Delta t}{2R} \beta_{i+\frac{1}{2},j+\frac{1}{2}}^\varepsilon (g_{i+1,j}^{+,n} + g_{i,j+1}^{-,n}) \right),
\end{aligned}$$

along with similar ones for $g_{i,j}^{\pm,n+1}$, too. From (4.2), it comes

$$\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon - \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon = \frac{\varepsilon^2 + \varepsilon(\varepsilon + \sigma_{i-\frac{1}{2},j+\frac{1}{2}} R)}{(\varepsilon + \sigma_{i-\frac{1}{2},j+\frac{1}{2}} R)(\varepsilon^2 + (\varepsilon + \sigma_{i-\frac{1}{2},j+\frac{1}{2}} R)^2)} \geq 0.$$

Define a (decreasing) function $\psi : \mathbb{R}^+ \rightarrow \mathbb{R}^+$,

$$\psi(x) \stackrel{def}{=} \frac{1}{\varepsilon + x} + \frac{x}{\varepsilon^2 + (\varepsilon + x)^2}, \quad \psi'(x) \leq 0 \text{ on } (0, +\infty),$$

then, since

$$\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon = \psi(\sigma_{i-\frac{1}{2},j+\frac{1}{2}} R),$$

we get the following bound:

$$\alpha_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon + \beta_{i-\frac{1}{2},j+\frac{1}{2}}^\varepsilon \leq \frac{1}{\varepsilon + \sigma_{min} R} + \frac{\sigma_{min} R}{\varepsilon^2 + (\varepsilon + \sigma_{min} R)^2}.$$

Hence $(f_{i,j}^{\pm,n+1}, g_{i,j}^{\pm,n+1})$ are nonnegative combinations of previous iterates if,

$$\left(\varepsilon + \frac{\Delta t}{2R} \right) \left(\frac{1}{\varepsilon + \sigma_{min} R} + \frac{\sigma_{min} R}{\varepsilon^2 + (\varepsilon + \sigma_{min} R)^2} \right) \leq 1, \quad (5.4)$$

$$\frac{\Delta t^2}{2R} \left(\frac{1}{\varepsilon + \sigma_{min} R} + \frac{\sigma_{min} R}{\varepsilon^2 + (\varepsilon + \sigma_{min} R)^2} \right) \leq 2\varepsilon R + \Delta t. \quad (5.5)$$

Conditions (5.4) and (5.5) are met if and only if,

$$\frac{\Delta t}{2R} \leq \sigma_{min} R \frac{\varepsilon^2 + \varepsilon \sigma_{min} R + (\sigma_{min} R)^2}{2\varepsilon^2 + 3\varepsilon \sigma_{min} R + 2(\sigma_{min} R)^2}, \quad \frac{\Delta t^2}{R(\varepsilon + \sigma_{min} R)} \leq 2\varepsilon R + \Delta t$$

and these hold as soon as (5.2) does. \square

REMARK 1. A sufficient condition for (5.2) is the heat equation's restriction:

$$2\Delta t \leq \sigma_{min} R^2 \quad (5.6)$$

LEMMA 5.2 (Conservation). *Let us assume that the initial data are nonnegative and that (5.2) holds. Then, the scheme (4.3) is bounded in L^1 and conservative :*

$$\|f^{+,n}\|_1 + \|f^{-,n}\|_1 + \|g^{+,n}\|_1 + \|g^{-,n}\|_1 = \|f^{+,0}\|_1 + \|f^{-,0}\|_1 + \|g^{+,0}\|_1 + \|g^{-,0}\|_1.$$

Proof. It suffices to add the lines of (4.3) and to sum over i and j . \square

LEMMA 5.3 (L^∞ bound). *Let initial data satisfy*

$$0 \leq f_{i,j}^{\pm,0} \leq M, \quad 0 \leq g_{i,j}^{\pm,0} \leq M.$$

Then, under the CFL (5.2),

$$\forall n \in \mathbb{N}, \quad 0 \leq f_{i,j}^{\pm,n} \leq M, \quad 0 \leq g_{i,j}^{\pm,n} \leq M.$$

Proof. The proof of Lemma 5.1 yields that, under (5.2), $f_{i,j}^{\pm,n+1}$ and $g_{i,j}^{\pm,n+1}$ are convex combination of previous iterates, giving the announced L^∞ bound. \square

REMARK 2. *These bounds hold even if the opacity σ isn't a (positive) constant.*

5.2. Uniform estimates in the case σ constant. We study rigorously the diffusive limit of (4.3) in order to prove that it is ‘‘asymptotic-preserving’’ (AP). Recall from (4.2) the coefficients,

$$\alpha^\varepsilon = \frac{1}{\varepsilon + \sigma R}; \quad \beta^\varepsilon = \frac{\sigma R}{\varepsilon^2 + (\varepsilon + \sigma R)^2}, \quad \text{for } \sigma \equiv \bar{\sigma} \in \mathbb{R}^+. \quad (5.7)$$

As σ is constant, (4.3) simplifies into,

$$\begin{pmatrix} 1 + \frac{\Delta t}{2\varepsilon R} & -\frac{\Delta t}{2\varepsilon R} & 0 & 0 \\ -\frac{\Delta t}{2\varepsilon R} & 1 + \frac{\Delta t}{2\varepsilon R} & 0 & 0 \\ 0 & 0 & 1 + \frac{\Delta t}{2\varepsilon R} & -\frac{\Delta t}{2\varepsilon R} \\ 0 & 0 & -\frac{\Delta t}{2\varepsilon R} & 1 + \frac{\Delta t}{2\varepsilon R} \end{pmatrix} \begin{pmatrix} f_{i,j}^{+,n+1} \\ f_{i,j}^{-,n+1} \\ g_{i,j}^{+,n+1} \\ g_{i,j}^{-,n+1} \end{pmatrix} = \begin{pmatrix} f_{i,j}^{+,n} \\ f_{i,j}^{-,n} \\ g_{i,j}^{+,n} \\ g_{i,j}^{-,n} \end{pmatrix} \quad (5.8)$$

$$+ \frac{\Delta t}{2R} \begin{pmatrix} \alpha^\varepsilon (f_{i-1,j-1}^{+,n} - f_{i,j}^{-,n}) - \beta^\varepsilon (f_{i-1,j-1}^{+,n} + f_{i,j}^{-,n} - g_{i,j-1}^{+,n} - g_{i-1,j}^{-,n}) \\ \alpha^\varepsilon (f_{i+1,j+1}^{-,n} - f_{i,j}^{+,n}) - \beta^\varepsilon (f_{i+1,j+1}^{-,n} + f_{i,j}^{+,n} - g_{i+1,j}^{-,n} - g_{i,j+1}^{+,n}) \\ \alpha^\varepsilon (g_{i+1,j-1}^{+,n} - g_{i,j}^{-,n}) + \beta^\varepsilon (f_{i,j-1}^{+,n} + f_{i+1,j}^{-,n} - g_{i+1,j-1}^{+,n} - g_{i,j}^{-,n}) \\ \alpha^\varepsilon (g_{i-1,j+1}^{-,n} - g_{i,j}^{+,n}) + \beta^\varepsilon (f_{i-1,j}^{+,n} + f_{i,j+1}^{-,n} - g_{i,j}^{+,n} - g_{i-1,j+1}^{-,n}) \end{pmatrix}$$

LEMMA 5.4. *Let σ be a positive constant: under the parabolic CFL restriction,*

$$2 \Delta t < \sigma_{\min} R^2, \quad (5.9)$$

the scheme (5.8) is TVD (total variation diminishing),

$$\begin{aligned} & TV(f^{+,n+1}) + TV(f^{-,n+1}) + TV(g^{+,n+1}) + TV(g^{-,n+1}) \\ & \leq TV(f^{+,n}) + TV(f^{-,n}) + TV(g^{+,n}) + TV(g^{-,n}). \end{aligned}$$

Proof. By linearity, the expression of $f_{i,j}^{+,n+1}$ in (5.3) in the proof of Lemma 5.1 is similar to the ones of $\delta f_{i+\frac{1}{2},j}^{+,n}$. Since (5.9) ensures that coefficients are nonnegative,

a triangle inequality brings,

$$\begin{aligned}
|\delta f_{i+\frac{1}{2},j}^{+,n+1}| &\leq \frac{1}{2\varepsilon R + 2\Delta t} \left((2\varepsilon R + \Delta t - \frac{\Delta t^2}{2R}(\alpha^\varepsilon + \beta^\varepsilon)) |\delta f_{i+\frac{1}{2},j}^{+,n}| \right. \\
&\quad + (\Delta t - \frac{\Delta t}{2R}(2\varepsilon R + \Delta t)(\alpha^\varepsilon + \beta^\varepsilon)) |\delta f_{i+\frac{1}{2},j}^{-,n}| \\
&\quad + (2\varepsilon R + \Delta t) \frac{\Delta t}{2R} (\alpha^\varepsilon - \beta^\varepsilon) |\delta f_{i-\frac{1}{2},j-1}^{+,n}| \\
&\quad + \frac{\Delta t^2}{2R} (\alpha^\varepsilon - \beta^\varepsilon) |\delta f_{i+\frac{3}{2},j+1}^{-,n}| \\
&\quad + (2\varepsilon R + \Delta t) \frac{\Delta t}{2R} \beta^\varepsilon (|\delta g_{i+\frac{1}{2},j-1}^{+,n}| + |\delta g_{i-\frac{1}{2},j}^{-,n}|) \\
&\quad \left. + \frac{\Delta t^2}{2R} \beta^\varepsilon (|\delta g_{i+\frac{1}{2},j}^{+,n}| + |\delta g_{i+\frac{1}{2},j+1}^{-,n}|) \right),
\end{aligned}$$

with similar expressions for $|\delta f_{i+\frac{1}{2},j}^{-,n}|$, $|\delta g_{i+\frac{1}{2},j}^{+,n+1}|$ and $|\delta g_{i+\frac{1}{2},j}^{-,n+1}|$. Adding,

$$\begin{aligned}
|\delta f_{i+\frac{1}{2},j}^{+,n+1}| + |\delta f_{i+\frac{1}{2},j}^{-,n+1}| + |\delta g_{i+\frac{1}{2},j}^{+,n+1}| + |\delta g_{i+\frac{1}{2},j}^{-,n+1}| &\leq \\
(1 - \frac{\Delta t}{2R}(\alpha^\varepsilon + \beta^\varepsilon)) (|\delta f_{i+\frac{1}{2},j}^{+,n}| + |\delta f_{i+\frac{1}{2},j}^{-,n}| + |\delta g_{i+\frac{1}{2},j}^{+,n}| + |\delta g_{i+\frac{1}{2},j}^{-,n}|) & \\
+ \frac{\Delta t}{2R}(\alpha^\varepsilon - \beta^\varepsilon) (|\delta f_{i-\frac{1}{2},j-1}^{+,n}| + |\delta f_{i+\frac{3}{2},j+1}^{-,n}| + |\delta g_{i+\frac{3}{2},j-1}^{+,n}| + |\delta g_{i-\frac{1}{2},j+1}^{-,n}|) & \\
+ \frac{\Delta t}{2R} \beta^\varepsilon (|\delta f_{i+\frac{1}{2},j-1}^{+,n}| + |\delta f_{i+\frac{3}{2},j}^{-,n}| + |\delta f_{i-\frac{1}{2},j}^{+,n}| + |\delta f_{i+\frac{1}{2},j+1}^{-,n}|) & \\
+ \frac{\Delta t}{2R} \beta^\varepsilon (|\delta g_{i+\frac{1}{2},j-1}^{+,n}| + |\delta g_{i-\frac{1}{2},j}^{-,n}| + |\delta g_{i+\frac{3}{2},j}^{+,n}| + |\delta g_{i+\frac{1}{2},j+1}^{-,n}|) &
\end{aligned}$$

and summing over i and j , we get, after shifting the indexes,

$$\begin{aligned}
\sum_{i,j} \left(|\delta f_{i+\frac{1}{2},j}^{+,n+1}| + |\delta f_{i+\frac{1}{2},j}^{-,n+1}| + |\delta g_{i+\frac{1}{2},j}^{+,n+1}| + |\delta g_{i+\frac{1}{2},j}^{-,n+1}| \right) & \\
\leq \sum_{i,j} \left(|\delta f_{i+\frac{1}{2},j}^{+,n}| + |\delta f_{i+\frac{1}{2},j}^{-,n}| + |\delta g_{i+\frac{1}{2},j}^{+,n}| + |\delta g_{i+\frac{1}{2},j}^{-,n}| \right). &
\end{aligned}$$

By the same token with variations in j instead of i , we get the claimed result. \square

Define $f_{\Delta x}^\pm, g_{\Delta x}^\pm$ the piecewise constant functions such that,

$$f^\pm(t, \mathbf{x}) = f_{i,j}^\pm, \quad g^\pm(t, \mathbf{x}) = g_{i,j}^\pm, \quad (5.10)$$

for $t \in [n\Delta t, (n+1)\Delta t)$, $\mathbf{x} \in ((i - \frac{1}{2})\Delta x, (i + \frac{1}{2})\Delta x) \times ((j - \frac{1}{2})\Delta x, (j + \frac{1}{2})\Delta x)$.

COROLLARY 5.5. *Under (5.9), and for bounded integrable nonnegative data, the approximate solutions (5.10) are uniformly bounded in $L^1 \cap L^\infty \cap BV([0, T] \times \mathbb{R}^2)$.*

5.3. Rigorous diffusive limit. We are now in position to state the main result of this section:

THEOREM 5.6 (Asymptotic-Preserving property). *Assume (5.9) holds and that initial data are independent of ε and smooth enough such that*

$$\exists C \in \mathbb{R}^+, \quad \|\Delta f^{+,0}\|_1 + \|\Delta f^{-,0}\|_1 + \|\Delta g^{+,0}\|_1 + \|\Delta g^{-,0}\|_1 \leq C,$$

then the sequences $(f_{i,j}^{\pm,n})$ and $(g_{i,j}^{\pm,n})$ are of uniformly bounded total variation and converge towards limits, denoted respectively $(f_{i,j}^{\pm})$ and $(g_{i,j}^{\pm})$ which satisfy:

$$f_{i,j}^{+,n} = f_{i,j}^{-,n} = \frac{1}{2}f_{i,j}^n, \quad g_{i,j}^{+,n} = g_{i,j}^{-,n} = \frac{1}{2}g_{i,j}^n,$$

where

$$f_{i,j}^{n+1} = f_{i,j}^n + \frac{\Delta t}{4\sigma R^2}(\mathfrak{g}_{i,j-1}^n + \mathfrak{g}_{i-1,j}^n + \mathfrak{g}_{i+1,j}^n + \mathfrak{g}_{i,j+1}^n - 4f_{i,j}^n) \quad (5.11)$$

$$\mathfrak{g}_{i,j}^{n+1} = \mathfrak{g}_{i,j}^n + \frac{\Delta t}{4\sigma R^2}(f_{i,j-1}^n + f_{i+1,j}^n + f_{i-1,j}^n + f_{i,j+1}^n - 4g_{i,j}^n). \quad (5.12)$$

Moreover, the ‘‘Maxwellian gap’’ decreases in time according to,

$$\forall n \in \mathbb{N}_*, \quad \|f^n - g^n\|_1 \leq \|f^0 - g^0\|_1 \exp\left(-\frac{2n\Delta t}{\sigma R^2}\right) + C R^2. \quad (5.13)$$

Adding both equations (5.11)-(5.12), we deduce the following result:

COROLLARY 5.7. *Under the same assumptions as Theorem 5.6, we have*

$$\rho_{i,j}^{n+1} = \rho_{i,j}^n + \frac{\Delta t}{4\sigma R^2}(\rho_{i,j-1}^n + \rho_{i,j+1}^n + \rho_{i-1,j}^n + \rho_{i+1,j}^n - 4\rho_{i,j}^n), \quad \rho^n = f^n + g^n.$$

along with $f^{\pm,n} = \rho^n/4 + O(R^2)$, $g^{\pm,n} = \rho^n/4 + O(R^2)$.

Proof. By the computations in the proof of Lemma 5.4, the sequences $(f_{i,j}^{\pm,n})$, and $(g_{i,j}^{\pm,n})$ are Cauchy sequences with respect to ε in ℓ^1 . Thus, when $\varepsilon \rightarrow 0$, they converge to some limits denoted respectively $(f_{i,j}^{\pm})$, and $(g_{i,j}^{\pm})$ and we can pass to the limit in (5.8). Hence as $\varepsilon \rightarrow 0$, by (4.4) and (4.7), we get that

$$\forall (i, j, n) \in \mathbb{Z}^2 \times \mathbb{N}, \quad f_{i,j}^{+,n+1} = f_{i,j}^{-,n+1}, \quad g_{i,j}^{+,n+1} = g_{i,j}^{-,n+1}.$$

Denoting $f_{i,j}^{\varepsilon n} = f_{i,j}^{\varepsilon+,n} + f_{i,j}^{\varepsilon-,n}$ and $g_{i,j}^{\varepsilon n} = g_{i,j}^{\varepsilon+,n} + g_{i,j}^{\varepsilon-,n}$, we obtain their equations by adding the first two and the last two lines in (5.8):

$$\begin{aligned} f_{i,j}^{\varepsilon n+1} &= f_{i,j}^{\varepsilon n} + \frac{\Delta t}{2R} \left(\alpha^\varepsilon (f_{i-1,j-1}^{\varepsilon+,n} - f_{i,j}^{\varepsilon-,n}) + \alpha^\varepsilon (f_{i+1,j+1}^{\varepsilon-,n} - f_{i,j}^{\varepsilon+,n}) \right) \\ &\quad - \frac{\Delta t}{2R} \left(\beta^\varepsilon (f_{i-1,j-1}^{\varepsilon+,n} + f_{i,j}^{\varepsilon-,n} - g_{i,j-1}^{\varepsilon+,n} - g_{i-1,j}^{\varepsilon-,n}) \right. \\ &\quad \left. + \beta^\varepsilon (f_{i,j}^{\varepsilon+,n} + f_{i+1,j+1}^{\varepsilon-,n} - g_{i+1,j}^{\varepsilon+,n} - g_{i,j+1}^{\varepsilon-,n}) \right); \end{aligned} \quad (5.14)$$

$$\begin{aligned} g_{i,j}^{\varepsilon n+1} &= g_{i,j}^{\varepsilon n} + \frac{\Delta t}{2R} \left(\alpha^\varepsilon (g_{i+1,j-1}^{\varepsilon+,n} - g_{i,j}^{\varepsilon-,n}) + \alpha^\varepsilon (g_{i-1,j+1}^{\varepsilon-,n} - g_{i,j}^{\varepsilon+,n}) \right) \\ &\quad + \frac{\Delta t}{2R} \left(\beta^\varepsilon (f_{i,j-1}^{\varepsilon+,n} + f_{i+1,j}^{\varepsilon-,n} - g_{i+1,j-1}^{\varepsilon+,n} - g_{i,j}^{\varepsilon-,n}) \right. \\ &\quad \left. + \beta^\varepsilon (f_{i-1,j}^{\varepsilon+,n} + f_{i,j+1}^{\varepsilon-,n} - g_{i,j}^{\varepsilon+,n} - g_{i-1,j+1}^{\varepsilon-,n}) \right). \end{aligned} \quad (5.15)$$

From the expressions (5.7),

$$\alpha^\varepsilon, \beta^\varepsilon \rightarrow \frac{1}{\sigma R}, \quad \text{when } \varepsilon \rightarrow 0.$$

Yet, passing into the limit we obtain both (5.11) and (5.12). If initially \mathbf{f} and \mathbf{g} were identical, they stay so. More precisely, let $D_{i,j}^n = \mathbf{f}_{i,j}^n - \mathbf{g}_{i,j}^n$ be the Maxwellian gap,

$$D_{i,j}^{n+1} = D_{i,j}^n \left(1 - \frac{2\Delta t}{\sigma R^2}\right) + \frac{\Delta t}{4\sigma R^2} (4D_{i,j}^n - D_{i,j-1}^n - D_{i-1,j}^n - D_{i+1,j}^n - D_{i,j+1}^n). \quad (5.16)$$

Hypotheses on initial data in Theorem 5.6 ensure that

$$\|\Delta \mathbf{f}^0\|_1 + \|\Delta \mathbf{g}^0\|_1 \leq C.$$

Moreover, from (5.11)–(5.12) and (5.9), we have

$$\begin{aligned} \|\Delta \mathbf{f}^{n+1}\|_1 &\leq \|\Delta \mathbf{f}^n\|_1 \left(1 - \frac{\Delta t}{\sigma R^2}\right) + \frac{\Delta t}{\sigma R^2} \|\Delta \mathbf{g}^n\|_1 \\ \|\Delta \mathbf{g}^{n+1}\|_1 &\leq \|\Delta \mathbf{g}^n\|_1 \left(1 - \frac{\Delta t}{\sigma R^2}\right) + \frac{\Delta t}{\sigma R^2} \|\Delta \mathbf{f}^n\|_1. \end{aligned}$$

As a consequence, for all $n \in \mathbb{N}$, we have $\|\Delta \mathbf{f}^n\|_1 + \|\Delta \mathbf{g}^n\|_1 \leq C$, so that

$$\sum_{i,j} |4D_{i,j}^n - D_{i,j-1}^n - D_{i-1,j}^n - D_{i+1,j}^n - D_{i,j+1}^n| \leq C.$$

By inserting this latter inequality into (5.16), taking modulus and summing,

$$\|D^{n+1}\|_1 = \sum_{i,j} \Delta x^2 |D_{i,j}^{n+1}| \leq \|D^n\|_1 \left(1 - \frac{2\Delta t}{\sigma R^2}\right) + C \frac{\Delta t}{\sigma},$$

holds for some constant $C \geq 0$. Applying a discrete Gronwall inequality,

$$\begin{aligned} \|D^n\|_1 &\leq \|D^0\|_1 e^{-2n\Delta t/(\sigma R^2)} + C \frac{\Delta t}{\sigma} \sum_{k=0}^{n-1} \left(1 - \frac{2\Delta t}{\sigma R^2}\right)^k \\ &\leq \|D^0\|_1 e^{-2n\Delta t/(\sigma R^2)} + \frac{C}{2} R^2. \end{aligned}$$

□

REMARK 3. *The bound (5.13) relates to (1.4) and means that, for constant opacity, $\|\mathbf{f} - \mathbf{g}\|_1$ is roughly of order Δx^2 when nonnegative initial data belong to $W^{2,1}(\mathbb{R}^2)$. Conversely, both $\|f^+ - f^-\|_1$ and $\|g^+ - g^-\|_1$ are of order ε , as in the 1D case, see [11, Lemma 8.4] and [14]. All in all, these will be similar when $\varepsilon \simeq O(R^2)$.*

6. Numerical assessments. Hereafter, some benchmarks for both (3.5) and (4.3) are presented, on a coarse 32×32 uniform Cartesian grid. The computational domain is the unit square $\Omega = (0, 1)^2$ with various boundary conditions.

6.1. Hyperbolic/kinetic scaling. Following [8, §5.1], the long-time stabilization of (1.3) can be considered in presence of a stiff, discontinuous opacity,

$$\sigma(\mathbf{x}) = 5 + 995 \cdot \chi \left(\max(|x - \frac{1}{2}|, |y - \frac{1}{2}|) < \frac{1}{4} \right),$$

with $\chi(A)$ the indicator function of a set A . A null initial data and an inflow boundary condition is prescribed on the left side by means of,

$$f^+(x = 0, \cdot) = g^-(x = 0, \cdot) = 1,$$

along with specular reflection on horizontal walls $y = 0$, $y = 1$, and outflow at $x = 1$. The macroscopic velocity field $\vec{v}(t, \mathbf{x})$ is defined as the following ratio,

$$\forall \mathbf{x} \in \Omega, \quad \vec{v}(t, \mathbf{x}) = \left(\frac{f^+(t, \mathbf{x}) - f^-(t, \mathbf{x})}{\rho(t, \mathbf{x})}, \frac{g^+(t, \mathbf{x}) - g^-(t, \mathbf{x})}{\rho(t, \mathbf{x})} \right), \quad \text{where } \rho \neq 0.$$

The scheme (3.5) was set with $\Delta t = 0.975\sqrt{2}\Delta x$, and iterated up to $T = 35$: see Fig. 6.1. Another benchmark consists in considering smooth, but quickly varying opacity,

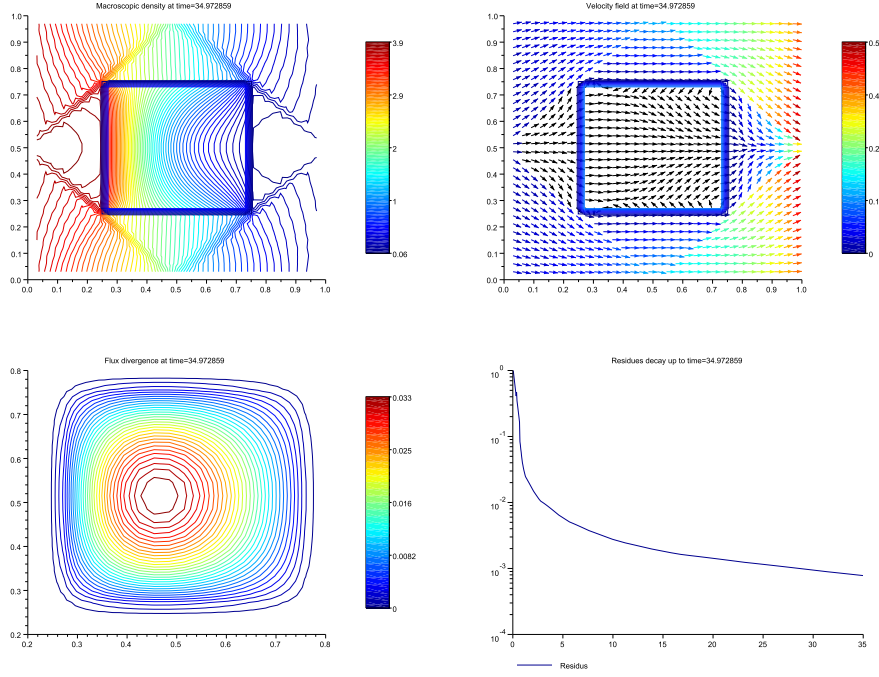


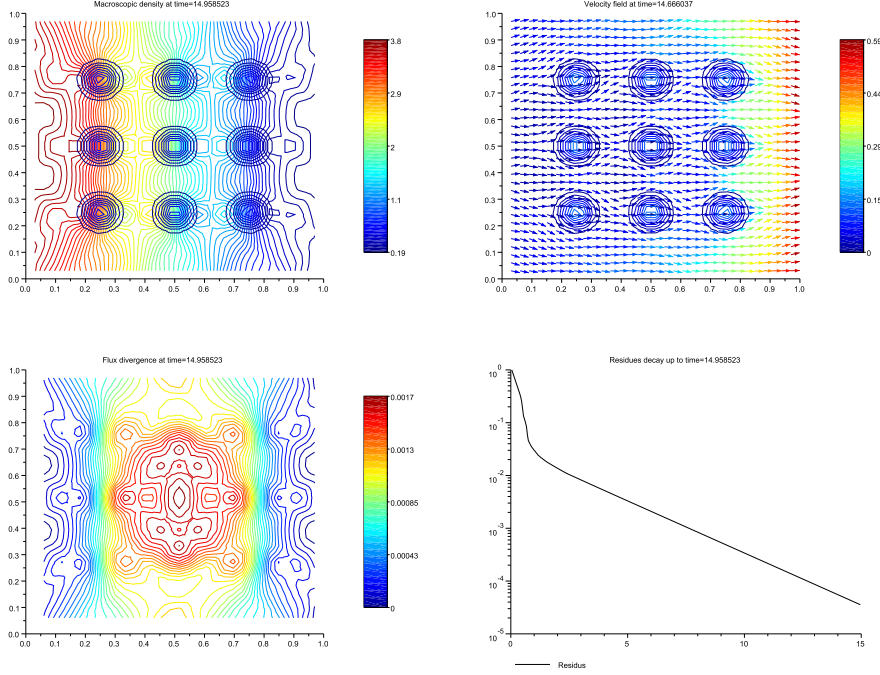
FIGURE 6.1. *Steady-state of (3.5) in presence of a square opaque zone.*

$$\begin{aligned} \sigma(\mathbf{x}) &= 5 + 195 \exp\left(-\gamma\left(\left(x - \frac{1}{4}\right)^2 + \left(x - \frac{1}{2}\right)^2 + \left(x - \frac{3}{4}\right)^2\right)\right) \\ &\quad \times \exp\left(-\gamma\left(\left(y - \frac{1}{4}\right)^2 + \left(y - \frac{1}{2}\right)^2 + \left(y - \frac{3}{4}\right)^2\right)\right), \quad \gamma = 400, \end{aligned}$$

with identical initial and boundary conditions. Results are displayed on Fig. 6.2. In particular, on both Figs. 6.1 and 6.2, a (second-order) centered approximation of the divergence of the macroscopic flux, $\text{div } \mathbf{J}(t, \mathbf{x})$ was displayed, so as to shed light on the ability of (3.5) to stabilize on a correct discretization of stationary regimes.

6.2. Diffusive/parabolic scaling. In order to validate the scheme (4.3), the same array of opaque Gaussian bumps was set, along with the parameter $\varepsilon = 10^{-5}$, outflow boundary conditions on each side, and Maxwellian (well-prepared) initial data,

$$\begin{aligned} \rho(t = 0, \mathbf{x}) &= \exp\left(-\nu\left(\left(x - 0.375\right)^2 + \left(x - 0.625\right)^2\right)\right) \\ &\quad \times \exp\left(-\nu\left(\left(y - 0.375\right)^2 + \left(y - 0.635\right)^2\right)\right), \quad \nu = 250. \end{aligned}$$

FIGURE 6.2. *Steady-state of (3.5) in a periodic array of obstacles.*

The scheme was iterated until $T = 15$ with the CFL condition (5.6): see Fig. 6.3. The macroscopic density is correctly confined inside the array of obstacles, showing how tiny the artificial dissipation of the IMEX scheme really is. The Maxwellian gap $|f - g|$ is locally of 10^{-3} , a value compatible with (5.13) because $\Delta x^2 \simeq 10^{-3}$, even in the vicinity of areas of strong variations of $\sigma(\mathbf{x})$; it smoothly decays with time. Beside, Δx^2 is also the order of accuracy for the centered discretization of the diffusion equation (4.8). The macroscopic velocity field \vec{v} is now rescaled,

$$\forall \mathbf{x} \in \Omega, \quad \vec{v}(t, \mathbf{x}) = \frac{1}{\varepsilon} \left(\frac{f^+(t, \mathbf{x}) - f^-(t, \mathbf{x})}{\rho(t, \mathbf{x})} \right), \quad \rho \neq 0.$$

A simpler benchmark consists in iterating (4.3) with a Gaussian opacity,

$$\forall \mathbf{x} \in \Omega, \quad \sigma(\mathbf{x}) = 5 + 15 \exp \left(-25 \left(\left| x - \frac{1}{2} \right|^2 + \left| y - \frac{1}{2} \right|^2 \right) \right),$$

with identical initial and outflow boundary conditions, up to $T = 0.1$: see Fig. 6.4.

7. Conclusion and outlook. The present paper showed that a high-quality, genuinely two-dimensional, numerical scheme (3.5), (4.3) can be deduced from the computations achieved in [4]. Such a strategy is by no means limited to isotropic scattering. Following [11, §10.3], an elementary model of chemotaxis dynamics is,

$$\partial_t f + \mathbf{v} \cdot \nabla f = \chi(\mathbf{v} \cdot \nabla S) \rho(t, \mathbf{x}) - f(\mathbf{x}, \mathbf{v}), \quad \mathbf{a} := \nabla S(\bar{\mathbf{x}}) \in \mathbb{R}^2, \quad (7.1)$$

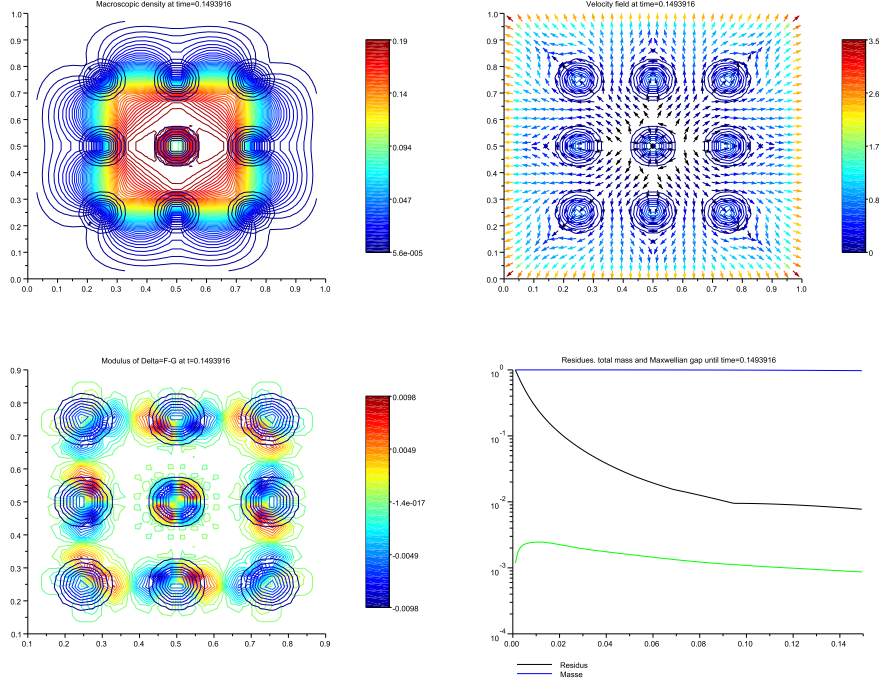


FIGURE 6.3. *Diffusive approximation (4.3) at $T = 15$, $\varepsilon = 10^{-5}$ in a periodic array of obstacles.*

where ∇S is “frozen” locally at a point $\bar{\mathbf{x}}$ and the biasing function $\chi \geq 0$ is normalized so as to get the standard 2D continuity equation:

$$\int_{\mathbb{S}^1} \chi(\mathbf{v}) \frac{d\mathbf{v}}{2\pi} = 1, \quad \partial_t \rho(t, \mathbf{x}) + \operatorname{div} \mathbf{J} = 0.$$

The analogue of the Laplace transform in (2.1) for steady-states $f(\mathbf{x}, \mathbf{v})$ reads,

$$f(\mathbf{x}, \mathbf{v}) = \chi(\mathbf{v}) \int_0^\infty \exp(-r) \rho(\mathbf{x} - r\mathbf{v}) dr = \chi(\mathbf{v}) \mathcal{L}_r(\tilde{\rho}_{\mathbf{x}, \mathbf{v}})[p = 1], \quad (7.2)$$

from which follows a new Fredholm equation, now involving the biasing function χ ,

$$\rho(\mathbf{x}) = \int_0^\infty \exp(-r) \left(\int_{\mathbb{S}^1} \chi(\mathbf{v}) \rho(\mathbf{x} - r\mathbf{v}) \frac{d\mathbf{v}}{2\pi} \right) dr. \quad (7.3)$$

To mimic some computations of [4], macroscopic steady-states should verify,

$$\forall r \in \mathbb{R}^+, \quad \rho(\mathbf{x}) = \int_{\mathbb{S}^1} \chi(\mathbf{v}) \rho(\mathbf{x} - r\mathbf{v}) \frac{d\mathbf{v}}{2\pi},$$

which means that our “biasing function” χ should also be the “Poisson kernel” of a certain elliptic differential operator that $\rho(\mathbf{x})$ solves. Indeed, $\rho(\mathbf{x} - r\mathbf{v})$ is “boundary data” on \mathbb{S}^1 , so $\rho(\mathbf{x})$ is the “solution value”. Accordingly, from [3, eqn (2.24)],

$$\rho(\mathbf{x}) = \int_0^{2\pi} \rho(\mathbf{x} + r e^{i\theta}) \frac{\exp(-\omega r \cos(\theta - \mu))}{\mathcal{I}_0(\omega r)} \frac{d\theta}{2\pi},$$

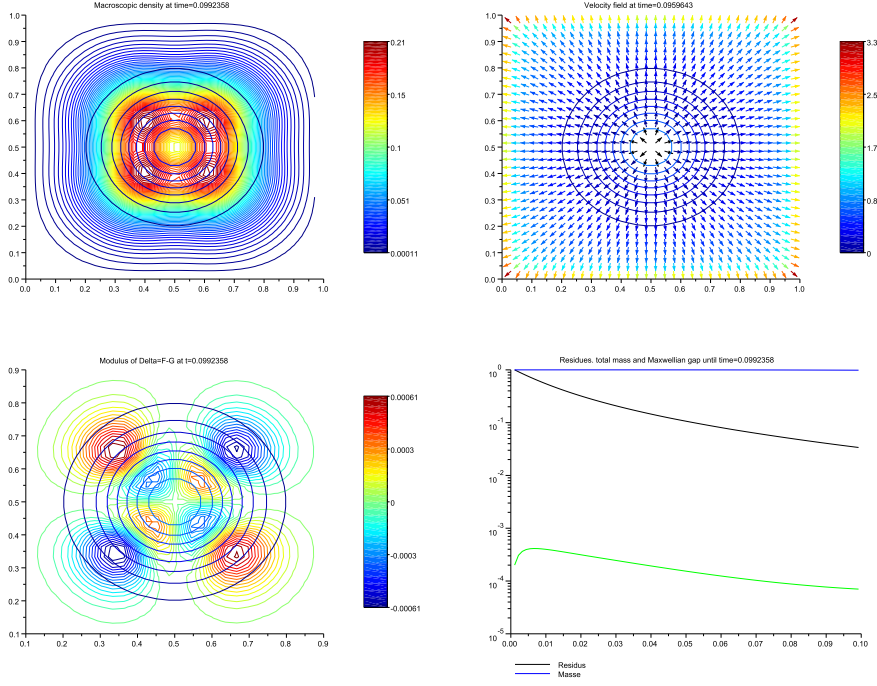


FIGURE 6.4. Diffusive approximation (4.3) at $T = 15$, $\varepsilon = 10^{-5}$ with a Gaussian opacity.

so that, by changing $\theta \rightarrow \theta - \pi$, one gets (see also [6, 10, 20])

$$\rho(\mathbf{x}) = \int_{-\pi}^{\pi} \rho(\mathbf{x} - r e^{i\theta}) \frac{\exp(\omega r \cos(\theta - \mu))}{\mathcal{I}_0(\omega r)} \frac{d\theta}{2\pi},$$

Pick, as the biasing function, (\mathcal{I}_0 , the modified Bessel function of index zero)

$$\chi(\mathbf{v} = e^{i\theta}) = \frac{\exp(\omega r \cos(\theta - \mu))}{\mathcal{I}_0(\omega r)} \geq 0, \quad \int_0^{2\pi} \frac{\exp(\omega r \cos \theta)}{\mathcal{I}_0(\omega r)} \frac{d\theta}{2\pi} = 1,$$

the normalization being a consequence of the “integral representation of Bessel functions”, see *e.g.* [3, eqn (3.1)], then such a kernel corresponds to drift-diffusion equation,

$$-\Delta \rho + \mathbf{a} \cdot \nabla \rho = 0, \quad \text{in the disk of radius } r > 0, \quad (7.4)$$

where (see again [3, eqns (2.1–3) and (2.12)]), for $\mu \in (0, 2\pi)$,

$$0 \leq \omega := \frac{\|\mathbf{a}\|}{2}, \quad \frac{\mathbf{a}}{2} = \omega(\cos \mu, \sin \mu) \in \mathbb{R}^2,$$

is the polar representation of the drift velocity $\mathbf{a} \in \mathbb{R}^2$ in (7.4). Accordingly, one can relate mesoscopic to macroscopic steady-states thanks to (7.2), and similar derivations as the ones performed in this article may lead to a “truly two-dimensional”, asymptotic-preserving (in diffusive scaling) discretization of (7.1), like (3.5) and (4.3).

Appendix A. S -matrix for Goldstein-Taylor model in 1D.

It might be interesting to recall some properties of “two-stream” one-dimensional (position-dependent) radiative transfer, already studied in [14], [11, §8.2] and [7, 9],

$$\partial_t f^\pm \pm \partial_x f^\pm = \sigma(x)(\rho/2 - f^\pm), \quad \rho = f^+ + f^-.$$

Macroscopic (diffusive) stationary regimes in 1D reduce to $\rho''(x) = 0$, *i.e.* constant or linear functions, and yield Case’s polynomial solutions, 1 and $x - v$. Accordingly, for $R = \Delta x/2$ and $f(x, v) = \alpha + \beta(x - v)$,

$$M = \begin{pmatrix} 1 & -(1 + \sigma R) \\ 1 & (1 + \sigma R) \end{pmatrix}, \quad \tilde{M} = \begin{pmatrix} 1 & -(1 - \sigma R) \\ 1 & (1 - \sigma R) \end{pmatrix},$$

so that,

$$|M| = 2(1 + \sigma R), \quad M^{-1} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ -\frac{1}{1 + \sigma R} & \frac{1}{1 + \sigma R} \end{pmatrix},$$

meaning that α is the average of incoming states, and

$$S(\sigma) = \tilde{M} M^{-1} = \frac{1}{1 + \sigma R} \begin{pmatrix} 1 & \sigma R \\ \sigma R & 1 \end{pmatrix}.$$

Such a S -matrix is “doubly-stochastic” because both its rows and columns add to unity and all its entries are positive when $\sigma R \geq 0$. Asymptotic limits are

$$S(\sigma) \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \text{ if } \sigma \rightarrow 0, \quad S(\sigma) \rightarrow \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \text{ if } \sigma \rightarrow +\infty.$$

The resulting well-balanced 1D time-marching scheme reads,

$$\begin{pmatrix} f_j^{+,n+1} \\ f_{j-1}^{-,n+1} \end{pmatrix} = \left(1 - \frac{\Delta t}{2R}\right) \begin{pmatrix} f_j^{+,n} \\ f_{j-1}^{-,n} \end{pmatrix} + \frac{\Delta t}{2R} S(\sigma_{j-\frac{1}{2}}) \begin{pmatrix} f_{j-1}^{+,n} \\ f_j^{-,n} \end{pmatrix}.$$

In parabolic scaling, the following decomposition holds,

$$S(\sigma) = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + \frac{\varepsilon}{\varepsilon + \sigma R} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix},$$

and brings back the well-known IMEX scheme originally written in [14],

$$\begin{aligned} & \begin{pmatrix} f_j^{+,n+1} \\ f_{j-1}^{-,n+1} \end{pmatrix} + \frac{\Delta t}{2\varepsilon R} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} f_j^{+,n+1} \\ f_{j-1}^{-,n+1} \end{pmatrix} \\ &= \begin{pmatrix} f_j^{+,n} \\ f_{j-1}^{-,n} \end{pmatrix} + \frac{\Delta t}{2R(\varepsilon + \sigma R)} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} f_{j-1}^{+,n} \\ f_j^{-,n} \end{pmatrix}. \end{aligned}$$

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