



HAL
open science

Ergodicity of the Ehrenfest wind-tree model

Alba Málaga Sabogal, Serge Troubetzkoy

► **To cite this version:**

Alba Málaga Sabogal, Serge Troubetzkoy. Ergodicity of the Ehrenfest wind-tree model. *Comptes Rendus. Mathématique*, 2016, 10.1016/j.crma.2016.08.008 . hal-01273212

HAL Id: hal-01273212

<https://hal.science/hal-01273212v1>

Submitted on 12 Feb 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Ergodicity of the Ehrenfest wind-tree model

Alba Málaga Sabogal^a, Serge Troubetzkoy^b

^a*Département de Mathématiques, Bâtiment 425, Faculté des Sciences d'Orsay, Université Paris-Sud 11, F-91405 Orsay Cedex.*

^b*Aix Marseille Université, CNRS, Centrale Marseille, I2M, UMR 7373, 13453 Marseille, France*

Received *****; accepted after revision +++++

Presented by

Abstract

We consider aperiodic wind-tree models, and show that for a generic (in the sense of Baire) configuration the wind-tree dynamics is ergodic in almost every direction.

Nous considérons un modèle apériodique de vent dans les arbres et nous montrons que pour une configuration générique (dans le sens de Baire) la dynamique de vent-arbre est ergodique dans presque-toute direction.

1. Introduction

In 1912 Paul et Tatyana Ehrenfest wrote a notable encyclopedia article on the foundations of statistical mechanics [EhEh]. The first chapter of this article “The Older Formulation of Statistico-mechanical investigations (Kineto-statistics of the Molecule)” discusses the work of Boltzmann and Maxwell on gas dynamics. In the Appendix to Section 5 of this chapter the Ehrenfests say “it seems advisable to explain” the work of Maxwell-Boltzmann “on a much-simplified model”. This model, now known as the Ehrenfest wind-tree model, is the subject of this article. In the Ehrenfest wind-tree model, a point particle (the “wind”) moves freely on the plane and collides with the usual law of geometric optics with an infinite number of irregularly placed identical square scatterers (the “trees”).

The second chapter of the Ehrenfests’ article “The Modern Formulation of Statistico-Mechanical Investigation (Kineto-Statistics of the Gas Model)” can

be viewed as the birth place of the term “ergodic”.¹ Our main result is the study of the wind-tree model in the framework of (infinite) ergodic theory. There is a natural first integral of the model, if we fix the initial direction, then orbits take only four directions. We show that for almost every value of this first integral the Ehrenfest wind-tree is ergodic for generic (in the sense of Baire) configurations. This continues our previous work where we have shown that the generic in the sense of Baire wind-tree model is recurrent ([Tr1]), minimal in almost every direction, and has a dense set of periodic points ([MSTr]).

The wind-tree model has been intensively studied by physicists, see for example [BiRo], [DeCoVB], [Ga], [HaCo], [VBHa], [WoLa] and the references therein. From the mathematical rigorous point of view, there have been many recent results about the dynamical properties of a periodic version of wind-tree models, scatterers are identical square obstacles one obstacle centered at each lattice point. The periodic wind-tree model has been shown to be re-

Email addresses: `alba.malaga@polytechnique.edu`
(Alba Málaga Sabogal), `serge.troubetzkoy@univ-amu.fr`
(Serge Troubetzkoy).

1. A nice discussion of the history of the birth of ergodic theory is given in the first chapter of the book [GaBoGe].

current ([HaWe], [HuLeTr],[AvHu]), to have abnormal diffusion ([DeHuLe],[De]), and to have an absence of ergodicity in almost every direction ([FrUl]); furthermore the periodic wind-tree model can not have a minimal direction. ² Periodic wind-tree models naturally yield infinite periodic translation surfaces, ergodicity in almost every direction for such surfaces have been obtained only in a few situations [HoHuWe], [HuWe], [RaTr].

We work in the following setup: the plane is tiled by one by one cells with corners on the lattice \mathbb{Z}^2 , inside each cell we place a square tree of a fixed size with the center chosen arbitrarily. Our main result is that for the generic in the sense of Baire wind-tree configuration, for almost all directions the wind-tree model is ergodic, is in stark contrast to the situation for the periodic wind-tree model. This result can be viewed as the confirmation of the ergodic hypothesis in the framework of the Ehrenfest wind-tree model.

Our proofs hold in a more general setting than the one described above, for example we can vary the size of the square, or use certain other polygonal trees; the class of possible extensions are the same as those discussed in [MSTr] in the framework of generic minimality in almost every direction.

The method of proof is by approximation by finite wind-tree models where the dynamics is well understood. There is a long history of proving results about billiard dynamics by approximation which began with the article of Katok and Zemlyakov [KaZe]. This method was used in several of the results on wind-tree models mentioned above [HuLeTr],[AvHu],[Tr1], see [Tr2] for a survey of some other usages in billiards. The idea of approximating infinite measure systems by compact systems was first studied in [MS].

2. Definitions and main result

Consider the plane \mathbb{R}^2 tiled by one by one closed square *cells* with corners on the lattice \mathbb{Z}^2 . Fix $r \in [1/4, 1/2)$. We consider the set of $2r$ by $2r$ squares, with vertical and horizontal sides, centered at (a, b) contained in the unit cell $[0, 1]^2$, this set is naturally parametrized by

$$\mathcal{A} := \{t = (a, b) : r \leq a \leq 1 - r, r \leq b \leq 1 - r\}$$

with the usual topology inherited from \mathbb{R}^2 . Our parameter space is $\mathcal{A}^{\mathbb{Z}^2}$ with the product topol-

² K. Frączek explained to us that this follows from arguments close to those in the article [Be].

ogy. It is a Baire space. Each parameter $g = (a_{i,j}, b_{i,j})_{(i,j) \in \mathbb{Z}^2} \in \mathcal{A}^{\mathbb{Z}^2}$ corresponds to a wind-tree table in the plane in the following manner: the tree inside the cell corresponding to the lattice point $(i, j) \in \mathbb{Z}^2$ is a $2r$ by $2r$ square with center at position $(a_{i,j}, b_{i,j}) + (i, j)$. The *wind-tree table* B^g is the plane \mathbb{R}^2 with the interiors of the union of these trees removed. Note that trees can intersect only at the boundary of cells.

The *billiard flow* ϕ_t is the unit speed free motion on the interior of B^g with elastic collision from the boundary of B^g (the boundary of the union of the trees). The phase space Ω^g of the billiard flow is thus the cartesian product of $B^g \times \mathbb{S}^1$ with inwards and outwards pointing unit vectors identified according to the elastic collision rule at the boundary of B^g . The billiard flow ϕ_t on the phase space preserves the volume measure $\mu \times \lambda$ where μ is the area measure on B^g and λ the length measure on \mathbb{S}^1 . Note that μ is an infinite measure.

For each θ let $[\theta]$ be the set of all possible directions under the billiard flow starting in direction θ , i.e. $[\theta] = \{\pm\theta, \pm(\pi - \theta)\}$. We will refer to the billiard flow restrict to the set $\{(x, \psi) \in \Omega^g : \psi \in [\theta]\}$ as the *billiard flow ϕ_t^θ in the direction θ* ; it preserves the measure $\mu \times d$ where d is the discrete measure on $[\theta]$.

A flow ψ_t preserving a measure m is called *ergodic* if for each Borel measurable $A, m(\psi_t(A) \Delta A) = 0 \forall t \in \mathbb{R}$ implies that $m(A) = 0$ or $\mu(A^c) = 0$. A map T preserving a measure n is called *ergodic* if for each Borel measurable set $A, n(T^{-1}A \Delta A) = 0$ implies that $n(A) = 0$ or $n(A^c) = 0$.

Theorem 2.1 *There is a dense G_δ subset \mathcal{G} of parameters $\mathcal{A}^{\mathbb{Z}^2}$ such that for each $g \in \mathcal{G}$ there is a dense G_δ subset of directions $\mathcal{H} \subset \mathbb{S}^1$ of full measure such that the billiard flow on Ω_g in the direction θ is ergodic every $\theta \in \mathcal{H}$.*

Note that we will use different cross-sections than those used in [MSTr]. Let $\mathcal{D}_n := \{(x, y) \in \mathbb{R}^2 : \max(|x|, |y|) = n\}$ and $\mathcal{D} := \bigcup_{n \geq 1} \mathcal{D}_n$. We will consider various first return maps of the billiard flow on the wind-tree table associated to a parameter g ,

$$T^g : \mathcal{D} \times \mathbb{S}^1 \rightarrow \mathcal{D} \times \mathbb{S}^1 T_\theta^g : \mathcal{D} \times [\theta] \rightarrow \mathcal{D} \times [\theta]$$

$$T_n^g : \mathcal{D}_n \times \mathbb{S}^1 \rightarrow \mathcal{D}_n \times \mathbb{S}^1 T_{n,\theta}^g : \mathcal{D}_n \times [\theta] \rightarrow \mathcal{D}_n \times [\theta].$$

We will apply this definitions only in the cases where \mathcal{D}_n do not intersect any tree.

The advantage of this cross-sections is that the maps T_θ^g and $T_{n,\theta}^g$ have natural invariant length measures which do not depend on the parameter g : ν and respectively ν_n . The measure ν is infinite, while

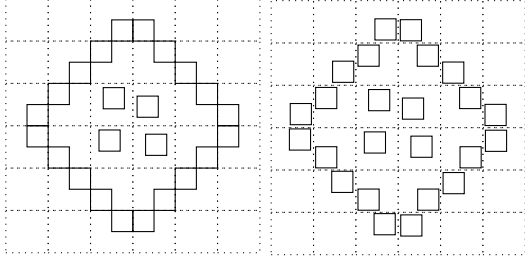


Figure 1. A 2-ringed con-figuration.

the measures ν_n are finite and we think of them as normalized.

For any positive integer N , we define $R_{\overline{N}}$ to be the closed rhombus $\{(x, y) : |x| + |y| \leq N + \frac{1}{2}\}$. Suppose that N is an integer satisfying $N \geq 2$. We will call a parameter f N -tactful if for each cell inside the rhombus $R_{\overline{N}}$, the corresponding tree is contained in the interior of its cell. We will call an N -tactful parameter f N -ringed, if the boundary of $R_{\overline{N}}$ is completely covered by trees (see Figure 1). Let E_N the set of pairs (i, j) so that the interior of the (i, j) -th cell is contained in $R_{\overline{N}}$.

For each tree $t \in \mathcal{A}$ let $U(t, \varepsilon)$ be the standard ε -neighborhood in \mathbb{R}^2 intersected with the interior of \mathcal{A} in \mathbb{R}^2 . For any parameter $g = (t_{i,j}) \in \mathcal{A}^{\mathbb{Z}^2}$, consider the open cylinder set $U_N(g, \varepsilon) = \prod_{(i,j) \in E_N} U(t_{i,j}, \varepsilon)$.

3. Proofs

We start by reducing the question to the ergodicity of the flow to the ergodicity the first return maps $T_{n,\theta}^g$. This is done in the following lemma.

Lemma 3.1 *Let g be a parameter that is N -tactful for all $N \geq 3$. For θ irrational, the following conditions are equivalent:*

- (i) $(\phi_\theta^g)_t$ is ergodic
- (ii) T_θ^g is ergodic
- (iii) $T_{n,\theta}^g$ is ergodic for all $n \geq 1$.

Proof.

(1 \implies 2) If B is a non trivial T_θ^g -invariant set, then $\bigcup_{t \in \mathbb{R}} (\phi_\theta^g)_t(B)$ is a non trivial $(\phi_\theta^g)_t$ -invariant set.

(2 \implies 1) Consider a non trivial $(\phi_\theta^g)_t$ invariant set C . Consider $C' := \bigcup_{t \in \mathbb{R}} (\phi_\theta^g)_t C$, clearly $\mu(C' \Delta C) = 0$ and C' is a $(\phi_\theta^g)_t$ -invariant set. Since the flow is a flow built under a piece-wise continuous bounded function, $C' \cap \mathcal{D}$ is a non trivial T_θ^g -invariant set.

(2 \implies 3) If A is a non trivial $T_{n,\theta}^g$ -invariant set, then $\bigcup_{k \in \mathbb{Z}} (T_{n,\theta}^g)^k(A)$ is a non trivial T_θ^g -invariant set.

(3 \implies 2) Suppose B is a non trivial T_θ^g -invariant set. We claim that $B_n := B \cap \mathcal{D}_n$ must be a non trivial $T_{n,\theta}^g$ -invariant set for some n . If not, then for each n , $\nu_n(B_n) = 0$ or $\nu_n(B_n^c) = 0$. Let $I := \{n \in \mathbb{N}^* : \nu_n(B_n^c) = 0\}$. Clearly I is non empty since $0 < \nu(B) = \sum_{n \in \mathbb{N}^*} \nu_n(B_n)$. Suppose $n \in I$, then since B_n has full measure in $\mathcal{D}_n \times [\theta]$, and since a set of positive measure of $\mathcal{D}_n \times [\theta]$ is mapped to $\mathcal{D}_{n+1} \times \theta$ we must have $n+1 \in I$. If $n \geq 2$ then the same holds for $n-1$, thus $I = \mathbb{N}^*$. This implies $\nu(B^c) = 0$, a contradiction. Thus B_n is a non trivial $T_{n,\theta}^g$ -invariant set for some n , i.e. $T_{n,\theta}^g$ is not ergodic for some n . \square

Proof of Theorem 2.1. By Baire's theorem the set of configurations which are N -tactful for all N is dense since for each N the set of all N -tactful configurations is an open dense set. Thus we can consider a countable dense set of parameters which are N -tactful for all N . By modifying the parameters we can assume that each one is N -ringed for a certain N still maintaining the density. Call this countable dense set $\{f_i\}$, with f_i being N_i -ringed. We also assume $N_{i+1} > N_i$. Suppose δ_i are strictly positive. Let

$$\mathcal{G} := \bigcap_{m \geq 1} \bigcup_{i \geq m} U_{N_i}(f_i, \delta_i).$$

See Figure 2 for a configuration close to a 2-ringed configuration. Clearly \mathcal{G} is a dense G_δ . We will show that the δ_i can be chosen in such a way that all the configurations in \mathcal{G} are ergodic in almost every direction.

For each $n \geq 1$ let $X_n := \mathcal{D}_n \times \mathbb{S}^1$, $X_n^\theta := \mathcal{D}_n \times [\theta]$, $\hat{\nu}_n := \nu_n \times \lambda$ and $\hat{\nu}_n^\theta := \nu_n$. Let $\{h_j\}_{j \geq 1}$ be a countable collection of continuous functions in $L^1(X_1, \hat{\nu}_1)$ for which the restriction to $L^1(X_1^\theta, \hat{\nu}_1^\theta)$ is dense for all θ . For each θ the measure space $(X_n^\theta, \hat{\nu}_n)$ is the union of eight isometric copies of the interval $[0, 2n(|\sin(\theta)| + |\cos(\theta)|)]$ (c.f figure 3).

For any n we define $h_j^n \in L^1(X_n, \hat{\nu}_n)$ by $h_j^n(s, \theta) := h_j(s/n, \theta)$ for $s \in [0, 2n(|\sin(\theta)| + |\cos(\theta)|)]$. For sake of simplicity we will drop the dependency on n and note $h_j = h_j^n$.

Now fix $g \in \mathcal{A}^{\mathbb{Z}^2}$ and let

$$S_{n,\ell}^g h_j(s, \theta) = \frac{1}{\ell} \sum_{k=0}^{\ell-1} h_j((T_{n,\theta}^g)^k(s, \theta)).$$

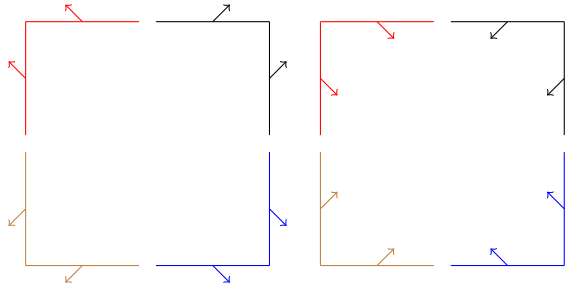


Figure 3. X_n^θ decomposes into eight “intervals”.

By the Birkhoff ergodic theorem, the maps $T_{n,\theta}^g$ are ergodic for all n and for almost every θ if and only if for all n and for almost all θ we have

$$S_{n,\ell}^g h_j(s, \theta) \rightarrow \int_{X_n^\theta} h_j(t) d\hat{\nu}_n(t)$$

as ℓ goes to infinity for all $j \geq 1$. Here the integral is over the set X_n^θ , thus we drop the θ dependence of the functions h_j from the notation.

Now fix i . Recall f_i is an N_i -ringed parameter. Let $n_i = \lfloor \frac{N_i-1}{2} \rfloor$. For any $1 \leq n \leq n_i$, D_n is included inside the ring and since f_i is N_i tactful D_n does not intersect the boundary of any tree. Because of the Kerckhoff-Masur-Smillie theorem [KeMaSm], the billiard inside the ring is ergodic for almost every direction, thus $T_{n,\theta}^{f_i}$ is ergodic for almost every θ . Thus we can find a positive integer ℓ_i , an open set $H_i \subset \mathbb{S}^1$ and sets $B_{n,i}^\theta \subset X_n^\theta$ so that $\hat{\nu}_n^\theta(B_{n,i}^\theta) > 1 - \frac{1}{i}$, $\lambda(H_i) > 1 - \frac{1}{i}$ and

$$\left| S_{n,\ell_i}^{f_i} h_j(s, \theta) - \int_{X_n^\theta} h_j(t) d\hat{\nu}_n(t) \right| < \frac{1}{i}$$

for all $s \in B_{n,i}^\theta$, $\theta \in H_i$, $n \leq n_i$, $1 \leq j \leq i$.

Now we would like to extend these estimates to the neighborhood $U_{N_i}(f_i, \delta_i)$ for a sufficiently small strictly positive δ_i . By the triangular inequality we have:

$$\begin{aligned} \left| S_{n,\ell_i}^g h_j(s, \theta) - \int_{X_n^\theta} h_j(t) d\hat{\nu}_n(t) \right| \leq \\ \left| S_{n,\ell_i}^g h_j(s, \theta) - S_{n,\ell_i}^{f_i} h_j(s, \theta) \right| + \\ \left| S_{n,\ell_i}^{f_i} h_j(s, \theta) - \int_{X_n^\theta} h_j(t) d\hat{\nu}_n(t) \right|. \end{aligned}$$

For any point (s, θ) of continuity of $(T_{n,\theta}^{f_i})^{\ell_i}$, the point $(T_{n,\theta}^g)^{\ell_i}(s, \theta)$ varies continuously with g in a small neighborhood of f_i ; thus we can find $\delta_i > 0$, an open set $\hat{H}_i \subset H_i$ and a set $\hat{B}_{n,i}^\theta \subset B_{n,i}^\theta$ so that that if $g \in U_{N_i}(f_i, \delta_i)$, then

$$\left| S_{n,\ell_i}^g h_j(s, \theta) - \int_{X_n^\theta} h_j(t) d\hat{\nu}_n(t) \right| < \frac{2}{i}$$

for all $s \in \hat{B}_{n,i}^\theta$, $\theta \in \hat{H}_i$, $n \leq n_i$, $1 \leq j \leq i$; and $\hat{B}_{n,i}^\theta$ and \hat{H}_i are both of measure larger than $1 - \frac{2}{i}$.

Suppose $g \in \mathcal{G} := \bigcap_{m=1}^\infty \bigcup_{i=m}^\infty U_{N_i}(f_i, \delta_i)$. Since $\lambda(\hat{H}_i) > 1 - 2/i$, the G_δ set $\mathcal{H} = \bigcap_{M=1}^\infty \bigcup_{i=M}^\infty \hat{H}_i$ has measure 1. Fix $\theta \in \mathcal{H}$, then there is an infinite sequence k_i such that $\theta \in \hat{H}_{k_i}$. Consider $\mathcal{B}_n^\theta = \bigcap_{M=1}^\infty \bigcup_{i=M}^\infty \hat{B}_{n,k_i}^\theta$. Since $\hat{\nu}_n^\theta(\hat{B}_{n,k_i}^\theta) > 1 - \frac{1}{k_i}$, it follows that $\hat{\nu}_n^\theta(\mathcal{B}_n^\theta) = 1$.

We can thus conclude that for λ -a.e. θ , for $\hat{\nu}_n$ -a.e. s , for each $j \geq 1$, for each $n \geq 1$

$$\lim_{k \rightarrow \infty} S_{n,\ell_{k_i}}^g(h_j(s, \theta)) \rightarrow \int_{X_n^\theta} h_j(t) d\hat{\nu}_n(t) \quad (1)$$

as $i \rightarrow \infty$. Since the h_j^θ are dense in $L^1(X_n^\theta, \hat{\nu}_n^\theta)$, Equation (1) together with the Birkhoff ergodic theorem imply that for each $n \geq 1$, $T_{n,\theta}^g$ is ergodic for all $\theta \in \mathcal{H}$. The ergodicity of the billiard flow in every direction in \mathcal{H} follows immediately from Lemma 3.1. \square

Acknowledgements

We gratefully acknowledge the support of ANR Perturbations and ANR GeoDyM as well as the grant APEX PAD attributed by the region PACA. This work has been carried out in the framework of the Labex Archimède (ANR-11-LABX-0033) and of the A*MIDEX project (ANR-11-IDEX-0001-02), funded by the “Investissements d’Avenir” French Government program managed by the French National Research Agency (ANR). ”.

References

- [AvHu] A. Avila and P. Hubert, *Recurrence for the wind-tree model* Annales de l’Institut Henri Poincaré - Analyse non linéaire.
- [Be] A.S. Besicovitch, *A problem on topological transformations of the plane. II.* Proc. Cambridge Philos. Soc. 47 (1951) 38–45.
- [BiRo] C. Bianca and L. Rondoni, *The nonequilibrium Ehrenfest gas: A chaotic model with flat obstacles?* Chaos 19 (2009) 013121.
- [De] V. Delecroix, *Divergent trajectories in the periodic wind-tree model* J. Mod. Dyn. 7 (2013) 1–29.

- [DeHuLe] V. Delecroix, P. Hubert and S. Lelièvre, *Diffusion for the periodic wind-tree model* Ann. Sci. ENS 47 (2014) 1085–1110.
- [DeCoVB] C. P. Dettmann, E.G.D. Cohen and H. van Beijeren *Statistical mechanics: Microscopic chaos from brownian motion?* Nature 401, 875 (1999) doi:10.1038/44759
- [EhEh] P. and T. Ehrenfest, *Begriffliche Grundlagen der statistischen Auffassung in der Mechanik* Encykl. d. Math. Wissensch. IV 2 II, Heft 6, 90 S (1912) (in German, translated in:) *The conceptual foundations of the statistical approach in mechanics*, (trans. Moravcsik, M. J.), 10-13 Cornell University Press, Itacha NY (1959).
- [FrUl] K. Frączek and C. Ulcigrai, *Non-ergodic \mathbb{Z} -periodic billiards and infinite translation surfaces* Invent. Math. 197 (2014) 241–298.
- [Ga] G. Gallavotti, *Divergences and the Approach to Equilibrium in the Lorentz and the Wind-Tree Models* Phys. Rev. 185 (1969) 308–322.
- [GaBoGe] G. Gallavotti, F. Bonetto and G. Gentile, *Aspects of Ergodic Qualitative and Statistical Theory of Motion* Springer 2004
- [HaWe] J. Hardy and J. Weber, *Diffusion in a periodic wind-tree model* J. Math. Phys. 21 (1980) 1802–1808.
- [HaCo] E.H. Hauge and E.G.D. Cohen, *Normal and Abnormal Diffusion in Ehrenfest's Wind-Tree Model* J. Math. Phys. 10 (1969) 397–414.
- [HuWe] P. Hubert and B. Weiss, *Ergodicity for infinite periodic translation surfaces* Compos. Math. 149 (2013) 1364–1380.
- [HoHuWe] P. Hooper, P. Hubert and B. Weiss, *Dynamics on the infinite staircase* Discrete Contin. Dyn. Syst. 33 (2013) 4341–4347.
- [HuLeTr] P. Hubert, Pascal, S. Lelièvre, and S. Troubetzkoy, *The Ehrenfest wind-tree model: periodic directions, recurrence, diffusion* J. Reine Angew. Math. 656 (2011) 223–244.
- [KaZe] A. Katok and A. Zemlyakov, *Topological transitivity of billiards in polygons* Math. Notes 18 (1975) 760–764.
- [KeMaSm] S. Kerckhoff, H. Masur, and J. Smillie, *Ergodicity of billiard flows and quadratic differentials*, Annals of Math. (2) 124 (1986), no. 2, 293–311.
- [MS] A. Málaga Sabogal, *Minimality of the Ehrenfest wind-tree model* Preprint 2015.
- [MSTr] A. Málaga Sabogal and S. Troubetzkoy, *Étude d'une famille de transformations préservant la mesure de $\mathbb{Z} \times \mathbb{T}$* Thèse Paris 11, 2014.
- [MaTa] H. Masur and S. Tabachnikov, *Rational billiards and flat structures* Handbook of dynamical systems, Vol. 1A, 1015–1089, North-Holland, Amsterdam, 2002.
- [RaTr] D. Ralston and S. Troubetzkoy, *Ergodic infinite group extensions of geodesic flows on translation surfaces* J. Mod. Dyn. 6 (2012) 477–497.
- [Tr2] S. Troubetzkoy, *Approximation and billiards* Dynamical systems and Diophantine approximation, 173–185, Semin. Congr., 19, Soc. Math. France, Paris, 2009.
- [Tr1] S. Troubetzkoy, *Typical recurrence for the Ehrenfest wind-tree model* J. Stat. Phys. 141 (2010) 60–67.
- [VBHa] H. Van Beyeren and E.H. Hauge, *Abnormal diffusion in Ehrenfest's wind-tree model* Physics Letters A 39, (1972) 397–398.
- [WoLa] W. Wood and F. Lado, *Monte Carlo calculation of normal and abnormal diffusion in Ehrenfest's wind-tree model* J. Comp. Physics 7 (1971) 528–546.