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# "Barchan" Dunes in the Lab

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**Abstract.** We demonstrate the feasibility of studying dunes in a laboratory experiment. It is shown that an initial sand pile, under a wind flow carrying sand, flattens and gets a shape recalling barchan dunes. An evolution law is proposed for the profile and the summit of the dune. The dune dynamics is shown to be shape invariant. The invariant shape, the "dune function" is isolated. © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

**Granular Media / Dunes / Barchans**

***Dunes de type "Barchanes" au laboratoire***

**Résumé.** *Nous montrons qu'il est possible d'étudier les dunes en laboratoire. Un tas de sable initial, soumis à un écoulement d'air chargé en sable, s'applatit et prend une forme qui rappelle celle d'une barchane. Nous proposons une loi d'évolution du profil et du sommet de la dune. Nous montrons que la dynamique de la dune est invariante de forme, et nous isolons cette forme invariante, "la fonction dune". © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS*

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## *Version française abrégée*

Depuis le travail fondateur de R.A. Bagnold sur la formation des dunes [**?**], de nombreuses mesures de terrain ont été effectuées dans les déserts. Elles montrent notamment l'existence, sous l'action d'un vent unidirectionnel, d'un type de dunes appelé barchane. Ces dunes sont caractérisées par une crête en forme de croissant, perpendiculaire à la direction du vent, et des bras sous le vent. Elles se déplacent en conservant une forme pratiquement constante. Différents modèles ont été proposés pour expliquer l'origine de ces dunes, mais il est généralement admis qu'elles doivent avoir une taille minimale pour exister, taille difficilement compatible avec celle des expériences habituellement réalisées en laboratoire.

Nous montrons dans cette Note qu'il est cependant possible d'obtenir, durant de longs transitoires, des dunes similaires dans un canal à vent de dimensions modestes. En effet, un tas de sable placé dans

**Note présentée par Yves POMEAU**

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un écoulement d'air chargé de sable peut, suivant les conditions expérimentales, prendre une forme caractéristique qui évoque celle d'une barchane (voir figure 2). La vitesse de vent, constante, doit être suffisamment grande pour que le phénomène de saltation puisse s'auto-entretenir mais rester inférieure au seuil au-delà duquel des grains initialement immobiles sont fluidisés. Une technique de profilométrie permet de mesurer quantitativement l'évolution au cours du temps d'un tas de sable placé au centre du canal. Aucun mouvement de sable n'est mis en évidence en dessous d'une certaine valeur du flux de sable ajouté à l'écoulement d'air. Au-delà, on observe que le tas évolue rapidement vers une forme caractéristique de dune qui demeure invariante au cours du temps (voir figure 3). Après un transitoire, la dune avance à vitesse constante et sa hauteur diminue en racine carrée du temps (voir figure 4).

A partir des données expérimentales, nous proposons une loi d'évolution du profil de la dune qui révèle cette forme invariante et nous montrons que cette loi peut être retrouvée de manière simple en réalisant un bilan de la masse transportée et perdue du tas de sable. Finalement, nous comparons les résultats obtenus avec les observations de terrain. Dans les déserts, la longueur de saltation est de l'ordre de 10 cm et l'extension longitudinale des dunes représente cent à mille fois cette longueur. La longueur de saltation a pu être réduite artificiellement à 1 cm dans l'expérience, permettant ainsi d'étudier des dunes au laboratoire. Elle reste cependant encore trop grande par rapport aux dunes qui sont observées, ce qui conduit sans doute à leur érosion.

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Dunes dynamics has strong impact on the ecology and the economy of sandy areas, but remains far from being understood. Since the single major work on sand dunes formation, written by R. A. Bagnold in 1941 [**?**], a world wide inventory of deserts has been developed in the fields by Sharp (1966) [**?**] and McKee (1979) [**?**], in application of aerial photography by Smith (1968) [**?**] and via Landsat imagery by Fryberger *et al.* (1979) [**?**] and Breed *et al.* (1979) [**?**], among others. Five basic types of dunes have been recorded : crescentic, linear, star, dome and parabolic. The most common dune is the crescentic, also called barchan. This type of dune forms under mono-directional winds. In that sense, barchans are also the most "simple" dunes. They are characterized by a crescentic crest normal to the wind direction, with downwind arms. The stronger the wind, the less open is the crescent. The windward (resp. leeward) face is concave (resp. convex). The barchans move over desert surfaces, while maintaining nearly constant shape. Various models [**?**, **?**, **?**, **?**, **?**] have been proposed, from cellular automata to two-phase (static and moving sand) models. However, if they qualitatively capture most of the fields observations, they call for more experimental data. On the one hand, field measurements are difficult to perform and often incomplete. On the other hand, it is believed that dunes have a minimal size of the order of the meter, not reducible to smaller laboratory scales.

In this Note, we show experimentally that an initial sand pile, under a wind flow carrying sand, flattens and gets a shape recalling barchan dune. After a short description of our experimental setup and protocol, we present first quantitative results about the observed dune patterns. We finally discuss why it is actually possible to observe dunes in the lab.

Fields observations indicate a very generic behavior of dunes essentially controlled by the wind direction and force, with little dependence on the details of the wind structure. Accordingly a very simple design has been chosen for the wind tunnel. It consists namely of two sections (figure 1(a)): the first one ($100\,\mathrm{mm}$ wide, $100\,\mathrm{mm}$ high, $730\,\mathrm{mm}$ long) is devoted to establish a regular wind; the second one ($230\,\mathrm{mm}$ wide, $175\,\mathrm{mm}$ high, $650\,\mathrm{mm}$ long) is open at its end and its floor is covered with $500\,\mu\mathrm{m}$ roughness sand-paper. The wind speed is constant and set below the "fluid threshold" and above the "impact threshold". These thresholds are defined as follows. For wind speeds above the "fluid threshold", grains are picked up from the surface and given a forward momentum, before being brought back to the surface under their own weight, after a typical "saltation length". If the surface is covered with sand, the grains loose most of their energy at the impact, but eject more than one grain on average. Once the saltation is initiated, it is self-sustained as long as the wind speed remains superior to the "impact threshold". For the considered sand, made up of mono-disperse $250\,\mu\mathrm{m}$ diameter glass beads, the fluid threshold $u_s^* \simeq 25\,\mathrm{cm/s}$ and the impact threshold $u_c^* \simeq 20\,\mathrm{cm/s}$ [**?**], where $u^*$ is the friction velocity as defined for a turbulent boundary layer [**?**].

The initial condition is a sand pile of volume $V_s$, centered in the wind tunnel. The wind is then set up and it is checked that no sand motion occurs until a sand flux $q_s$ is added to the wind at the top of the entrance of the second channel section; (in the following $q_s$ is the vertically integrated sand flow rate per spanwise length unit). In the present study, we report on three experiments $E_{1,2,3}$ with respectively $q_{s_1} = 1.25 \pm 0.25\,\mathrm{gs^{-1}m^{-1}}$ and $V_{s_1} = 30\,\mathrm{cm^3}$, $q_{s_2} = q_{s_1}$ and $V_{s_2} = 20\,\mathrm{cm^3}$, $q_{s_3} = 5 \pm 0.25\,\mathrm{gs^{-1}m^{-1}}$ and $V_{s_3} = V_{s_1}$. The quantitative sand pile evolution, is obtained by profilometry : A sinusoidal light intensity is projected onto the experimental field and a CCD camera records the field images from the top at regular time interval. The local streamwise phase gradient of the light intensity is directly proportional to the local slope (figure 1(b)). The recorded images are processed in order to obtain the topography $h(x, y)$.

After a transient of the order of 5 minutes, the typical crescent shape of the dune (figure 2), with arms downwind and a slip-face on the leeward side appears. A slight disturbance of this face actually induces avalanching. The crescent crest is rather open as expected in low wind conditions. Under the present experimental conditions, the dune is eroded until full removal of the initial amount of sand. Figure 3 displays the evolution of the streamwise profile $h^+(x,t)$ going through the dune summit. The sand pile first rapidly decreases in size to evolve towards a characteristic shape with a concave upwind side and a convex downwind side. Figure 3(b) displays more frequent time steps after the transient regime, scaled by the summit abscissa $x_s$ and height $h_s$. Once the dune profile is reached, its shape remains the same up to rescaling. Figure 4 displays the evolution of $x_s$ and $h_s$. The time has been scaled by $t^* = \frac{\rho_s}{q_s} h_s(0)^2$, where $\rho_s = 1.57\,\mathrm{g/cm^3}$ is the sand bulk density, $q_s$ the injected sand flux rate, and $h_s(0)$ the maximum height at the initial condition. This time scale $t^*$, here suggested by a dimensional analysis, is naturally recovered in the resolution of the mass balance equation (see later). The dunes obtained in the three experiments exhibit the same evolution, with identical scaled lifetimes. After the initial transient, the dunes propagate at constant velocity and their height decay like a square root of time, as shown in inset of figure 4(b). Altogether, the dune profile follows an evolution given by:

$$h^+(x,t) = h_s(t)\mathcal{D}\left(\frac{x - x_s}{h_s}\right),$$

$$\text{with} \quad \frac{h_s(t)}{h_s(0)} = 1 - \alpha\sqrt{\frac{t}{t^*}},$$

$$\text{and} \quad \frac{x_s(t) - x_s(0)}{x_s(t^*) - x_s(0)} = \frac{t}{t^*};$$

where $\alpha$ is a dimensionless constant $\mathcal{D}$, and the "dune function", is the invariant shape of the dune profile.

These evolution laws can easily be recovered by considering mass transport and losses of the sand pile. Let us consider an infinitesimal streamwise layer of the dune with profile $h^+(x,t)$. We assume the airflow carrying sand to be confined to a layer of constant height $H$. We also assume the sand flux to be uniform in height, so that the sand flux per height unit is $\frac{q_s}{H}$. The expected proportionality between the sand transport $\rho_s h_s v_s$ due to the dune motion at velocity $v_s$ through a cross section at the abscissa of the maximum height, and the sand flux through a section of height $h_s$ outside the dune gives $\rho_s h_s v_s \propto \frac{q_s}{H} h_s$, thus the observed constant velocity. Considering now the mass per spanwise length unit $M = A\rho_s h_s^2$, where $A$ is the dimensionless area under $\mathcal{D}$, we compute its decay rate. On one hand the balance of erosion and deposition rates must be proportional to the sand flux per height unit times the dune cross section. On the other hand, if the wind charged in sand is confined in a layer of height $H$, when passing over the dune it is accelerated by a factor of $H/(H - h_s)$ which may enforce the erosion, so that:

$$\frac{dM}{dt} = 2A\rho_s \frac{dh_s}{dt} h_s \propto -\frac{q_s}{H}\frac{H}{H-h_s} h_s,$$

$$\text{thus} \quad \frac{d\tilde{h_s}}{dt}(\tilde{H} - \tilde{h_s}) \propto -\frac{q_s}{\rho_s h_s^2(0)},$$

where $\tilde{h_s} = h_s/h_s(0)$; $\tilde{H} = H/h_s(0)$. Integrating with the initial condition $\tilde{h_s}(0) = 1$, one has the relation:

$$\tilde{h_s}^2 - 2\tilde{H}\tilde{h_s} + 2\tilde{H} - 1 = \alpha^2 \frac{t}{t^*},$$

with $\alpha^2$ a positive proportionality constant. The decreasing solution with time is:

$$\frac{h_s(t)}{h_s(0)} = \tilde{H} - \sqrt{\alpha^2 \frac{t}{t^*} + (\tilde{H} - 1)^2}.$$

The simpler expression obtained experimentally is recovered when $\tilde{H} = 1$, in agreement with the visual observation that the injected sand flux extends on a height of the same order of the initial sand pile. This specific feature may be different in nature.

How is it that we could observe dunes at a much smaller scale than in nature *with the same kind of sand*? In deserts, dunes have to grow from flat initial conditions. As already pointed out by R. A. Bagnold [**?**], the self accumulation process responsible for dunes building is efficient if the wind speed is high enough to charge the wind in sand prior to the dunes field. For a typical wind speed of $25\,\mathrm{km/h}$, at one meter above ground, the friction velocity is $u^* \simeq 1\,\mathrm{m/s}$ and the saltation length is $l_s \simeq 10\,\mathrm{cm}$ [**?**]. A typical dune streamwise extension is of the order of a hundred to a thousand times the saltation length. Such ratios are clearly out of reach of the lab experiment. Yet the above results clearly demonstrate the feasibility of dune investigation in a lab, at least during a long transient. Moreover, the downwind motion of the dune reveals a transport mechanism similar to the one observed in nature, in which the windward face is eroded, while the leeward face accumulates sand until avalanches set up. Having dealt with low wind, artificially charged in sand, we have lowered the saltation length down to $l_s \simeq 1\,\mathrm{cm}$. This is more than one tenth of the sand pile streamwise extension, but it is small enough to let saltation occurs on the windward face of the dune and accordingly to let the basic dynamics mechanisms take place. Since there must actually be not just a single saltation length but a distribution of them around an average, the main difference between nature and our experiment is that, in nature saltation jumps an order of magnitude larger than the averaged value still transport sand on the dune, whereas in our experiment, the grains are lost for the dune. This difference may explain why our experimental dunes erode so fast.

Altogether, we believe that the initial sand pile evolves according to the same elementary erosion and deposition mechanisms as those involved in a stationary dune dynamics in nature. Together with the robustness of the dune shape underlined by Werner's elementary model [**?**], it leads us to conclude to the relevance of the dune function obtained here. Whether the laboratory dunes are exactly barchan dunes, in a sense which should be precised, needs further investigation of both field and experimental data. Beyond the above quantitative results, the present work has proved the feasibility of investigating small dunes convenient for lab investigations. It calls for further studies under various wind conditions, with different sand types and opens a new kind of investigations in desert studies.

**Acknowledgements.** We thank D. Bonamy, E. Bertin, for helpful discussions and P. Meininger for technical support.

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## FIGURE CAPTIONS

Figure l : set up and measurement technique (a) Schematic drawing of the wind tunnel, with sand injection and measurement set up : (1),(2) first and second wind tunnel sections ; (3) ventilator ; (4) honeycomb ; (5) sand injection ; (6) CCD camera ; (7) parallel lighting ; (8) light intensity modulating grid ; (b) A typical top view of a dune with the modulated lighting. The local streamwise phase gradient is directly proportional to the local slope.

Figure 2 : A dune in the lab. Typical evolution of the initial sand pile (a) exposed to the wind charged in sand coming from left upper corner of the picture. (a),(b),(c),(d) are separated by 5 minutes time intervals.

Figure 3 : Evolution of dune profile in experiment $E_2$. (a) From initial condition to complete removal (time interval between curves is 2 min.) (b) Scaled profiles after transient (time interval between dotted curves is 1 min.) The invariant shape , the "dune function", $\mathcal{D}$ is in dark line.

Figure 4 : Evolution of dune summit parameters. (a) summit abscissa ; (b) summit height with log-log plot in inset. Labels are ($\bullet$) for experiment $E_1$, $(+)$ for $E_2$, $(\times)$ for $E_3$.

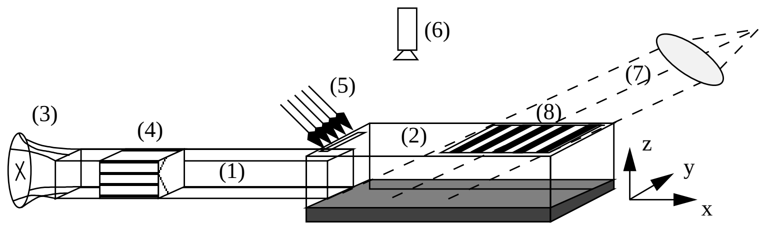
## LEGENDE DES FIGURES

Figure 1 : Dispositif expérimental et technique de mesure (a) Schéma du canal à vent, comportant l'injection du sable et le dispositif de mesure : (1),(2) première et deuxième section du canal à vent ; (3) ventilateur ; (4) nid d'abeille ; (5) injection de sable ; (6) caméra CCD ; (7) éclairage parallèle ; (8) grille de modulation de l'intensité lumineuse ; (b) Vue de dessus type en présence de l'éclairage modulé. Le gradient longitudinal local est directement proportionel à la pente locale.

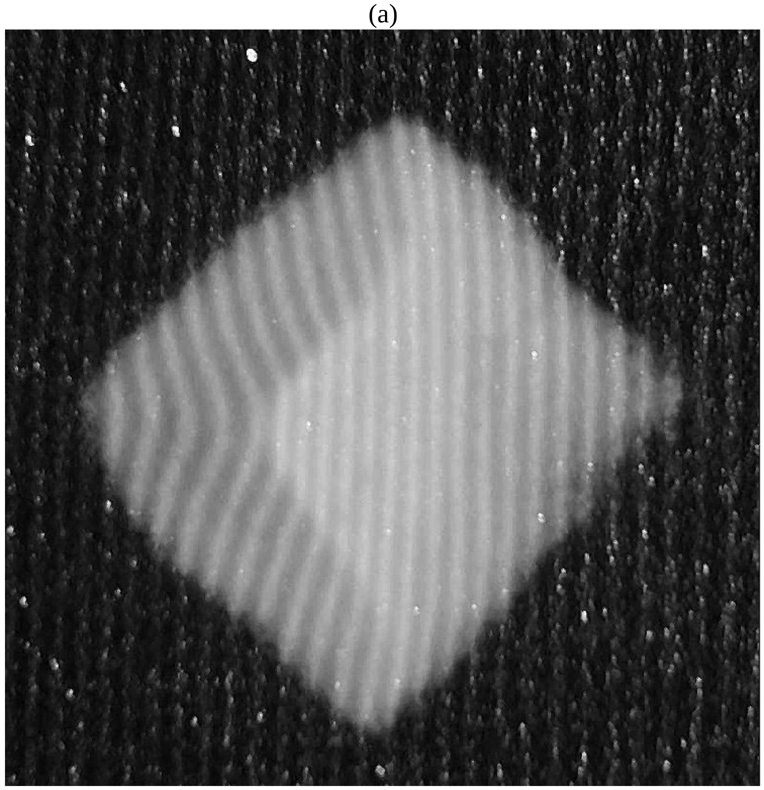
Figure 2 : Une dune en laboratoire. Evolution typique du tas de sable initial (a) exposé a un vent chargé en sable provenant du coin supérieur gauche de la photographie. (a),(b),(c),(d) sont séparés par des intervalles de temps de 5 minutes.

Figure 3 : Evolution du profil de dune dans l'expérience $E_2$. (a) De la condition initiale à sa complète disparition (l'intervalle de temps entre les courbes est de 2 min.) (b) Profils mis à l'échelle, après le premier transitoire (l'intervalle de temps entre les courbes est de 1 min.) La forme invariante, la "fonction dune", $\mathcal{D}$ est en trait noir continu.

Figure 4 : Evolution temporelle des paramètres du sommet de la dune. (a) abscisse du sommet ; (b) hauteur du sommet avec une représentation log-log en encart. Les labels sont ($\bullet$) pour l'expérience $E_1$, $(+)$ pour $E_2$, $(\times)$ pour $E_3$.




(a)



(b)

Figure 1

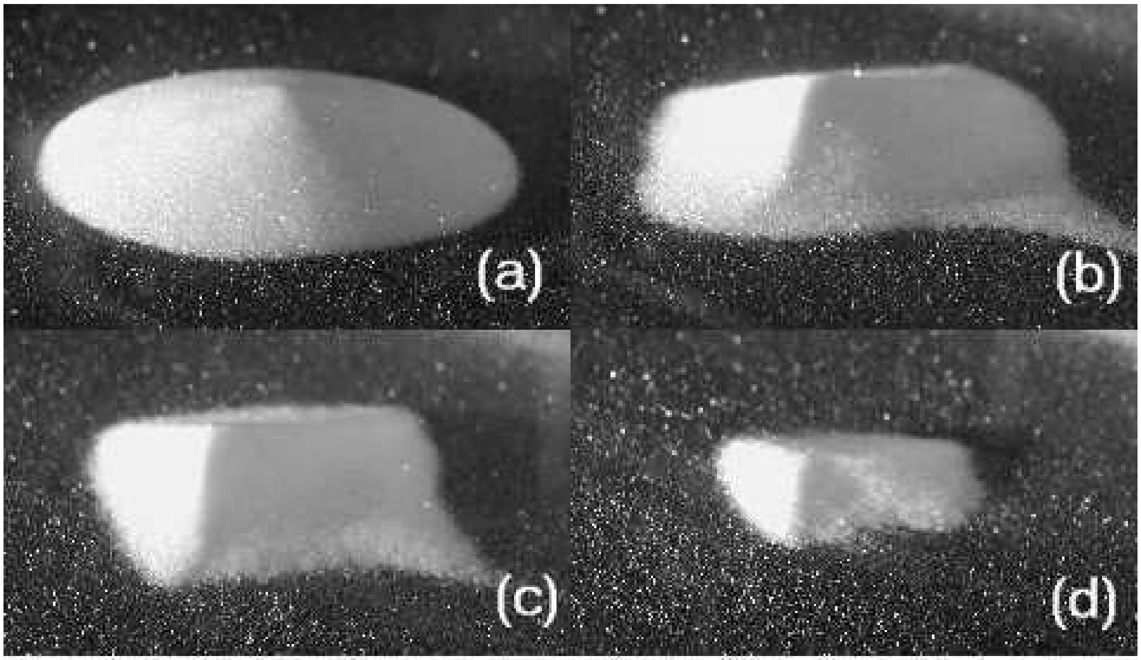
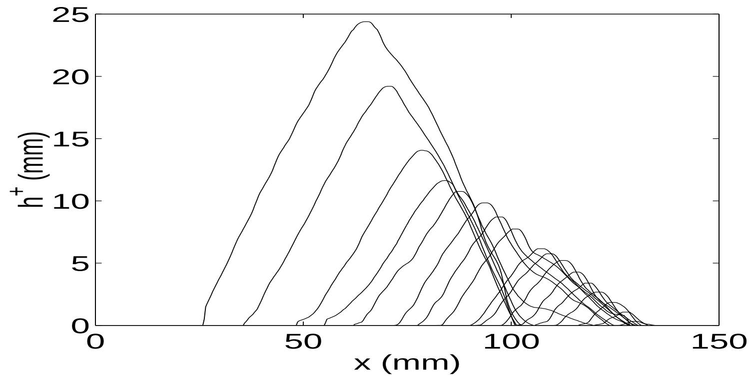
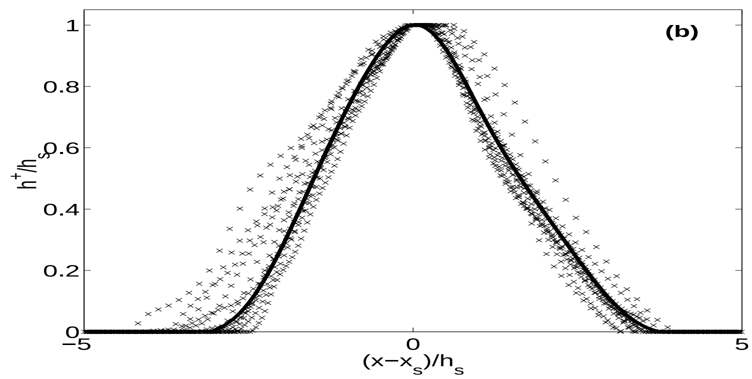



Figure 2

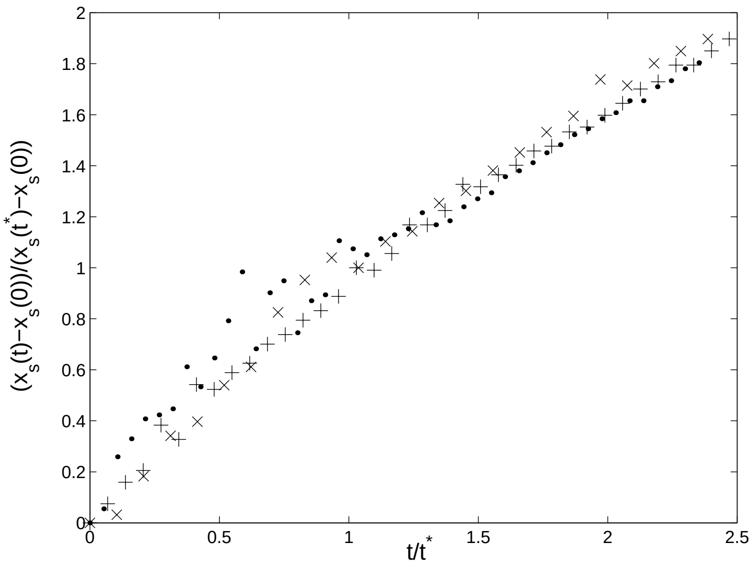



(a)

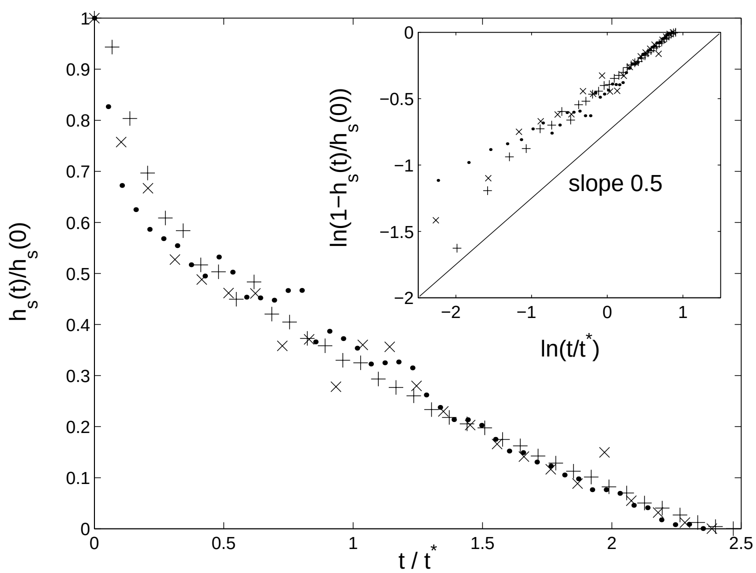



(b)

Figure 3


$(x_s(t)-x_s(0))/(x_s(t^*)-x_s(0))$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.5
1
1.5
2
2.5
$t/t^*$

(a)


$h_s(t)/h_s(0)$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
$t / t^*$
$\ln(1-h_s(t)/h_s(0))$
$\ln(t/t^*)$
slope 0.5
0
−0.5
−1
−1.5
−2
−2
−1
0
1

(b)

Figure 4