Multi-time distribution of periodic TASEP

Jinho Baik

University of Michigan

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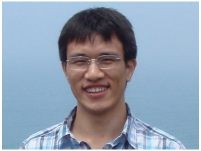
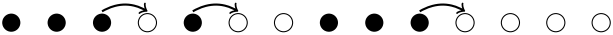
Joint work with Zhipeng Liu (Courant Institute)



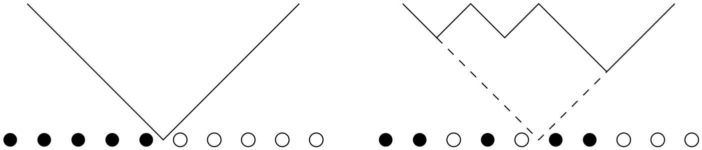
1. (Baik, Liu) Fluctuations of TASEP on a ring in relaxation time scale. arXiv:1605.07102. CPAM
2. (Liu) Height fluctuations of stationary TASEP on a ring in relaxation time scale. arXiv:1610.04601. AIHP
3. (Baik, Liu) Multi-time distribution of periodic TASEP (in preparation)

Introduction

TASEP (Totally Asymmetric Simple Exclusion Process



Height function $H(s,t)$: Associate ● ○ with ╲╱ and associate ○ ● with ╱╲



- TASEP is an example of a model in the KPZ universality class
- height fluctuations, spatial correlations, time correlations 1:2:3
- Height function $H(s,t)$ for $s \in \mathbb{R}$, $t \in \mathbb{R}_+$

$$h_T(\gamma,\tau) := \frac{H(c_1 T^{2/3}\gamma, T\tau) - (c_2 T + c_3 T^{2/3})}{c_4 T^{1/3}}$$

- What is the limiting two–dimensional process?

$$(\gamma,\tau) \mapsto h(\gamma,\tau) = \lim_{T\to\infty} h_T(\gamma,\tau)$$

One-point distribution

- Tracy–Widom distributions (from random matrix theory: fluctuations of the largest eigenvalue) and their variations
- Depends on the initial condition
- GUE Tracy-Widom for step initial condition
- GOE Tracy-Widom for initial condition
- Proved for "integrable/solvable" models in the KPZ class
- TASEP (totally asymmetric simple exclusion process), ASEP, certain directed polymers, the KPZ equation, ...

Equal–time

- Fix τ and consider $\gamma \mapsto h(\gamma, \tau)$
- Airy_2 process for step initial condition (random matrix interpretation: the largest eigenvalue process of Hermitian matrix Brownian motion)
- Airy_1 process for flat initial condition (no random matrix here)
- Proved for TASEP and some zero temperature directed polymers
- But not for ASEP, positive temperature directed polymers, and KPZ equation yet.
- Prähofer, Spohn, Johansson, Sasamoto, Borodin, Ferrari (mid 2000), Matetski, Quastel, Remenik (2016), ...

- Slow decorrelation [Ferrari 2008]
- Two-time distribution (not rigorous) [Dotsenko 2013]
- Two-time distribution (Brownian directed last passage percolation) [Johansson 2016]
- Short time ($\tau_2/\tau_1 \to 1$) and long time ($\tau_2/\tau_1 \to 0$) asymptotics of time covariance $\mathrm{Cov}(h(0,\tau_1), h(0,\tau_2))$ [Ferrari, Spohn 2016]
- Tail of two-time distribution: $p_{\tau_2/\tau_1}(x_1, x_2)$ for large positive x_1 and arbitrary x_2 in the short time and long time limits [de Nardis, Le Doussal 2016]

This talk: Multi-time distribution for periodic TASEP

Periodic TASEP

- L period
- N number of particles per period
- $\rho = \frac{N}{L}$ particle density (ρ fixed, L, N large)

- t not too large: infinite TASEP (KPZ dynamics)
- t too large: finite TASEP (equilibrium dynamics)
- crossover: relaxation time scale $t = O(L^{3/2})$

- Gwa and Spohn 1992
- Derrida and Lebowitz 1998
- Priezzhev, Povlotsky, Golinelli, Mallick
- Prolhac 2013–2016

Results

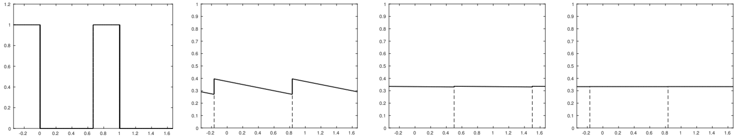
Periodic step initial condition ●●●○○○○●●●○○○○●●●○○○○

1. Multi-time, multi-position joint distribution in the limit $t = O(L^{3/2})$
2. A discussion on the one-point distribution

** One-point distribution for three (periodic step, flat, stationary) initial conditions: Prolhac & Baik–Liu, independently, 2016

Density profile and shocks

- $t, L, N \to \infty$ with $t = O(L^{3/2})$ and $\rho = N/L$ fixed
- There are shocks traveling with speed $1 - 2\rho$. In this talk, assume $\rho = 1/2$



- Discontinuity $O(Lt^{-1})$
- When $t = O(L^{3/2})$, the discontinuity is same order as the height flcutations

Fluctuation result

- $t, L, N \to \infty$ with $t = O(L^{3/2})$ and $\rho = N/L$ fixed
- Joint height distribution $\mathbb{P}\left(\cap_{j=1}^{m}\{H(s_j, t_j) \le h_j\}\right)$
- Position $s_j = \gamma_j L$ with $\gamma_i \in [0, 1]$
- Time $t_j = 2\tau_j L^{3/2}$ satisfying $0 < \tau_1 < \cdots < \tau_m$
- Height $h_j = \frac{1}{2} t_j - x_j L^{1/2}$ with $x_j \in \mathbb{R}$

Theorem

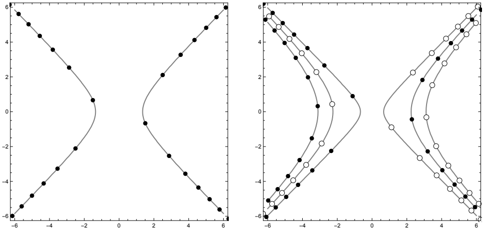
$$\mathbb{P}\left(\cap_{j=1}^{m}\{H(s_j, t_j) \le h_j\}\right) \to \mathbf{F}(x_1, \cdots, x_m; (\gamma_1, \tau_1), \cdots, (\gamma_m, \tau_m))$$

- $\mathbf{F}(x_1, \cdots, x_m) = \frac{1}{(2\pi\mathrm{i})^m} \oint \cdots \oint \mathbf{C}(\mathbf{z})\mathbf{D}(\mathbf{z}) \prod_{i=1}^m \frac{\mathrm{d}z_i}{z_i}$
- Nested circles $|z_m| < \cdots < |z_1| < 1$
- $\mathbf{C}(\mathbf{z})$ has simple poles at $z_i = z_{i+1}$

$$\mathbf{C}(\mathbf{z}) = \left[\prod_{i=1}^{m-1} \frac{z_i}{z_{i+1} - z_i}\right] \left[\prod_{i=1}^{m} \frac{\mathbf{A}_i(z_i)}{\mathbf{A}_{i-1}(z_i)}\right] \mathbf{Q}(\mathbf{z})$$

where $\mathbf{A}_i(z) = e^{-\sqrt{\frac{2}{\pi}}\left(x_i \,\mathrm{Li}_{3/2}(z) + \tau_i \,\mathrm{Li}_{5/2}(z)\right)}$. $\mathbf{Q}(\mathbf{z})$ is analytic, $\mathbf{Q}(0) \neq 0$, and it does not depend on x_i, τ_i, γ_i.

- $\mathbf{D}(\mathbf{z})$ has an isolated singularity at $z_i = 0$
- $\mathbf{D}(\mathbf{z}) = \det(\mathbf{1} - \mathbf{K})$ where $\mathbf{K} = \mathbf{K_1 K_2}$
- Give $|z| < 1$, consider the zeros of the equation $e^{-w^2/2} = z$
- Denote the set of zeros by $L_z \cup R_z$.



- $(m = 3)$ $\mathbf{K_1} : \ell^2(R_{z_1}) \oplus \ell^2(L_{z_2}) \oplus \ell^2(R_{z_3}) \to \ell^2(L_{z_1}) \oplus \ell^2(R_{z_2}) \oplus \ell^2(L_{z_3})$

- Using $\xi_i \in L_{z_i}$ and $\eta_i \in R_{z_i}$, the matrix kernel is of form (for $m = 5$)

$$\mathbf{K_1} = \begin{bmatrix} \mathbf{K_1}(\xi_1,\eta_1) & \mathbf{K_1}(\xi_1,\xi_2) & & & \\ \mathbf{K_1}(\eta_2,\eta_1) & \mathbf{K_1}(\eta_2,\xi_2) & & & \\ & & \mathbf{K_1}(\xi_3,\eta_3) & \mathbf{K_1}(\xi_3,\xi_4) & \\ & & \mathbf{K_1}(\eta_4,\eta_3) & \mathbf{K_1}(\eta_4,\xi_4) & \\ & & & & \mathbf{K_1}(\xi_5,\eta_5) \end{bmatrix}$$

- Set $\mathbf{F}_i(w) = \exp\left(-\frac{1}{3}\tau_i w^3 + \frac{1}{2}\gamma_i w^2 + x_i w\right)$

- The 2×2 blocks are ($\mathrm{Re}(\xi) < 0$ and $\mathrm{Re}(\eta) > 0$)

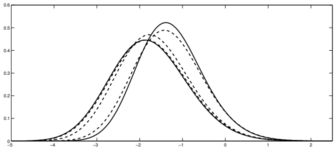
$$\begin{bmatrix} \mathbf{K_1}(\xi,\eta) & \mathbf{K_1}(\xi,\xi') \\ \mathbf{K_1}(\eta',\eta) & \mathbf{K_1}(\eta',\xi') \end{bmatrix} = \begin{bmatrix} \frac{\mathbf{F}_i(\xi)}{\mathbf{F}_{i-1}(\xi)} & 0 \\ 0 & \frac{\mathbf{F}_i(\eta')}{\mathbf{F}_{i+1}(\eta')} \end{bmatrix} \begin{bmatrix} f(\xi) & 0 \\ 0 & g(\eta') \end{bmatrix} \begin{bmatrix} \frac{1}{\xi-\eta} & \frac{1}{\xi-\xi'} \\ \frac{1}{\eta'-\eta} & \frac{1}{\eta'-\xi'} \end{bmatrix} \begin{bmatrix} h(\xi) & 0 \\ 0 & j(\eta') \end{bmatrix}$$

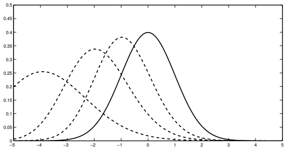
where f, g, h, j depend also on z, z' but do not depend on x_i, τ_i, γ_i

One-point distribution $\mathbf{F}(x;(\gamma,\tau))$

Formal computation shows:

- $\tau \to 0$: $\mathbf{F}(\tau^{1/3}x + \frac{\gamma^2}{4\tau^{2/3}};(\gamma,\tau)) \to \begin{cases} \mathbf{F}_{GUE}(x) & \gamma \neq 1/2 \\ \mathbf{F}_{GUE}(x)^2 & \gamma = 1/2 \end{cases}$
- $\tau \to \infty$: $\mathbf{F}(\frac{\sqrt{2}\tau^{1/6}}{\pi^{1/4}}(x+\tau);(\gamma,\tau)) \to \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-y^2/2}\mathrm{d}y$





Conjecture

For m-point multi-time distribution, if the $\epsilon \to 0$ limit of

$$\mathbf{F}(\epsilon^{1/3}\tau_1^{1/3}x_1, \cdots, \epsilon^{1/3}\tau_m^{2/3}x_m; (\epsilon^{2/3}\tau_1^{2/3}\gamma_1, \epsilon\tau_1), \cdots, (\epsilon^{2/3}\tau_m^{2/3}\gamma_m, \epsilon\tau_m))$$

exists, we expect that it is the limiting multi-time distribution of the usual infinite TASEP, and hence presumably of the KPZ universality class.

Very brief discussion on the proof (finite time formula)

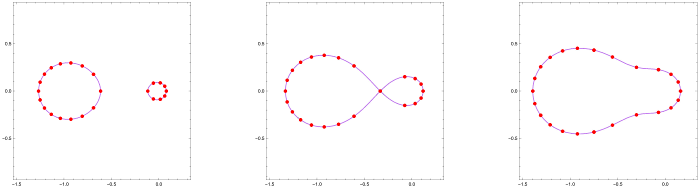
- The limit is obtained from an exact finite-time formula, which has a parallel structure
- We compute the multi-time distribution of particle locations $x_k(t)$
- TASEP in the configuration space $\mathcal{X}_{L,N} = \{x_N < \cdots < x_1 < x_N + L\}$
- Step 1. Find the transition probability $\mathbb{P}_Y(X; t)$ explicitly using coordinate Bethe ansatz method
- Step 2. Compute the multi-point distribution explicitly by summing the transition probability
- Step 3. Simplify the formula for the periodic step initial condition

- Schütz (1997): Computed transition probability for TASEP using coordinate Bethe ansatz
- Rákos and Schütz (2005): Using Schütz's formula, reproduced Johansson's result (the Fredholm determinant formula for the 1-point distribution for step initial condition)
- Borodin, Ferrari, Prähofer and Sasamoto (2007–2008): Using Schütz's formula, obtained Fredholm determinant formula for equal-time processes (and space-like points). They also extended the method to a few other models.
- Tracy and Widom (2008–2009): ASEP, 1-point distribution

For X and Y in $\{x_N < \cdots < x_1 < x_N + L\}$,

$$\mathbb{P}_Y(X;t) = \oint \det\left[\frac{1}{L}\sum_w \frac{w^{i-j+1}(w+1)^{-x_i+y_j-i+j}e^{tw}}{w+\rho}\right]_{N\times N} \frac{\mathrm{d}z}{2\pi \mathrm{i} z}$$

Sum over the roots of $w^N(w+1)^{L-N} = z^L$



Compare with Schütz formula:

$$\mathbb{P}_Y^{\text{TASEP}}(X;t) = \det\left[\oint w^{i-j+1}(w+1)^{-x_i+y_j-i+j}e^{tw}\right]_{N\times N}$$

$$\mathbb{P}_Y\left(\cap_{i=1}^m \{x_{k_i}(t_i) \ge a_i\}\right)$$
$$= \sum \cdots \sum \mathbb{P}_Y(X^{(1)}; t_1)\,\mathbb{P}_{X^{(1)}}(X^{(2)}; t_2 - t_1) \cdots \mathbb{P}_{X^{(m-1)}}(X^{(m)}; t_m - t_{m-1})$$

The ith sum is over all $x_N^{(i)} < \cdots < x_1^{(i)} < x_N^{(i)} + L$ satisfying $x_{k_i}^{(i)} \ge a_i$. The result is

$$\frac{1}{(2\pi \mathrm{i})^m} \oint \cdots \oint \mathcal{C}(\mathbf{z}, \mathbf{k}) \mathcal{D}_Y(\mathbf{z}, \mathbf{k}, \mathbf{t}, \mathbf{a}) \prod_{i=1}^m \frac{\mathrm{d}z_i}{z_i}$$

where

$$\mathcal{D}_Y(\mathbf{z}) = \det\left[\sum_{w_1,\cdots,w_m} \frac{w_1^{-i}(w_1+1)^{y_i+i-1} w_m^{-j}}{\prod_{\ell=2}^m (w_\ell - w_{\ell-1})} \prod_{\ell=1}^m \frac{w_\ell(w_\ell+1)}{L(w_\ell+\rho)} g_\ell(w_\ell)\right]_{N\times N}$$

with

$$g_\ell(w) = \frac{w^{k_\ell}(w+1)^{-a_\ell - k_\ell - 1} e^{t_\ell w}}{w^{k_{\ell-1}}(w+1)^{-a_{\ell-1} - k_{\ell-1} - 1} e^{t_{\ell-1} w}}$$

Step 3. Simplify further for step initial condition

Set $y_i = -i + 1$. Then

$$\mathcal{D}_Y(\mathbf{z}) = \det\left[\sum_{w_1,\cdots,w_m} \frac{w_1^{-i} w_m^{-j}}{\prod_{\ell=2}^m (w_\ell - w_{\ell-1})} \prod_{\ell=1}^m g_\ell(w_\ell)\right]_{N\times N}$$

This simplifies to a Fredholm determinant. Here we need to take $|z_i| < r_0 := \rho^\rho(1-\rho)^{1-\rho}$ for all i.

Slightly longer discussion

Step 2

Inserting the Schütz-like formual

$$P_Y(X;t) = \oint \det\left[\frac{1}{L}\sum_w \frac{w^{i-j+1}(w+1)^{-x_i+y_j-i+j}e^{tw}}{w+\rho}\right]_{N\times N}\frac{\mathrm{d}z}{2\pi \mathrm{i}z}$$

from Step 1 into

$$\begin{aligned}&\mathbb{P}_Y\left(\cap_{i=1}^m\{x_{k_i}(t_i)\ge a_i\}\right)\\ &=\sum\cdots\sum \mathbb{P}_Y(X^{(1)};t_1)\,\mathbb{P}_{X^{(1)}}(X^{(2)};t_2-t_1)\cdots\mathbb{P}_{X^{(m-1)}}(X^{(m)};t_m-t_{m-1})\end{aligned}$$

(sums over all $x_N^{(i)} < \cdots < x_1^{(i)} < x_N^{(i)} + L$ satisfying $x_{k_i}^{(i)} \ge a_i$), we need to evaluate

$$\sum_{\{x_N<\cdots<x_1<x_N+L\}\cap\{x_k\ge a\}} \det\left[w_i^j(w_i+1)^{-x_j-j}\right]\det\left[(w_i')^{-j}(w_i'+1)^{x_j+j}\right]$$

where $w_i^N(w_i+1)^{L-N} = z^L$, and $(w_i')^N(w_i'+1)^{L-N} = (z')^L$

Key lemma:

$$\sum_{\{x_N<\cdots<x_1<x_N+L\}\cap\{x_k\geq a\}} \det\left[w_i^j(w_i+1)^{-x_j-j}\right]\det\left[(w_i')^{-j}(w_i'+1)^{x_j+j}\right]$$

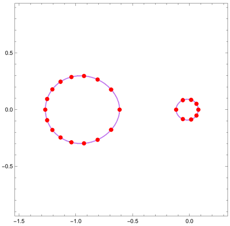
$$=\left(\frac{z'}{z}\right)^{(k-1)L}\left(1-\left(\frac{z}{z'}\right)^L\right)^{N-1}\left[\prod_{j=1}^N\left(\frac{w_j'}{w_j}\right)^{N-k+1}\frac{(w_j'+1)^{a-1-N+k}}{(w_j+1)^{a-2-N+k}}\right]\det\left[\frac{1}{w_{i'}'-w_i}\right]$$

when $w_i^N(w_i+1)^{L-N}=z^L$, and $(w_i')^N(w_i'+1)^{L-N}=(z')^L$

For the step initial condition, the Step 2 formula becomes

$$\mathcal{D}_Y(\mathbf{z}) = \det\left[\sum_{w_1,\cdots,w_m} \frac{w_1^{-i} w_m^{-j}}{\prod_{\ell=2}^m (w_\ell - w_{\ell-1})} \prod_{\ell=1}^m g_\ell(w_\ell)\right]_{N\times N}$$

where the sum is over all roots $w_i^N (w_i+1)^{L-N} = z_i^L$.



- Take $|z_i| < r_0$
- Expand the det of the sum as sums of dets
- Sums are over N-tuples of roots $w_i^{(j)}$, $j = 1, \cdots, N$.
- For $w_i^{(j)}$ on the right circle, use hole-particle duality.
- The result is the series expansion of a Fredholm determinant.

Thank you for attention