

ON THE BLOCK COUNTING PROCESS AND THE FIXATION LINE OF EXCHANGEABLE COALESCENTS

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Abstract

We study the block counting process and the fixation line of exchangeable coalescents. Formulas for the infinitesimal rates of both processes are provided. It is shown that the block counting process is Siegmund dual to the fixation line. For exchangeable coalescents restricted to a sample of size n and with dust we provide a convergence result for the block counting process as n tends to infinity. The associated limiting process is related to the frequencies of singletons of the coalescent. Via duality we obtain an analog convergence result for the fixation line of exchangeable coalescents with dust. The Dirichlet coalescent and the Poisson–Dirichlet coalescent are studied in detail.

Keywords: block counting process; coming down from infinity; Dirichlet coalescent; duality; dust; exchangeable coalescent; fixation line; Poisson–Dirichlet coalescent

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1 Introduction

Coalescent processes have attracted the interest of many researchers over the last decades, mainly in population genetics and probability. Most results in coalescent theory concern coalescents with multiple collisions independently introduced by Pitman [23] and Sagitov [26]. Less is known for the full class of exchangeable coalescents $\Pi = (\Pi_t)_{t \geq 0}$ allowing for simultaneous multiple collisions of ancestral lineages. Note that Π is a Markovian process taking values in the space \mathcal{P} of partitions of $\mathbb{N} := \{1, 2, \dots\}$. Schweinsberg [29] showed that every exchangeable coalescent Π can be characterized by a finite measure Ξ on the infinite simplex

$$\Delta := \{x = (x_r)_{r \in \mathbb{N}} : x_1 \geq x_2 \geq \dots \geq 0, |x| := \sum_{r=1}^{\infty} x_r \leq 1\}. \quad (1)$$

Exchangeable coalescents are therefore called Ξ -coalescents. The aim of this article is to provide some more information on the block counting process and the fixation line of the Ξ -coalescent and on the relation between these two processes. We therefore briefly recall the definition of the block counting process and turn afterwards to the fixation line.

For $t \geq 0$ let N_t denote the number of blocks of Π_t . It is well known that $N := (N_t)_{t \geq 0}$ is a Markovian process with state space $S := \mathbb{N} \cup \{\infty\}$, called the block counting process of Π . We use the notation $N_t^{(n)}$ for the number of blocks of Π_t restricted to a sample of size $n \in \mathbb{N}$. The block counting process has been studied intensively in the literature with a main focus on coalescents with multiple collisions (Λ -coalescents). We will revisit some of its properties throughout this article.

The definition of the fixation line is more involved. As in [29] decompose $\Xi = \Xi(\{0\})\delta_0 + \Xi_0$ with δ_0 the Dirac measure at $0 \in \Delta$ and Ξ_0 having no atom at 0. For $x = (x_r)_{r \in \mathbb{N}} \in \Delta$ define $(x, x) := \sum_{r=1}^{\infty} x_r^2$ and $\nu(dx) := \Xi_0(dx)/(x, x)$. One possible definition of the fixation line is based on the lookdown construction going back to Donnelly and Kurtz [2, 3]. For some further information on the lookdown construction we refer the reader to [1]. Imagine a population consists of countably many individuals distinguished by their levels. The level of an individual is a positive integer, and the individual at time $t \geq 0$ at level $i \in \mathbb{N}$ is

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denoted by (t, i) . In the following we use Schweinsberg's Poisson process construction [29, Section 3]. Define $\mathbb{N}_0 := \{0, 1, 2, \dots\}$ and, for every $x = (x_r)_{r \in \mathbb{N}} \in \Delta$, let P_x be the law of a sequence $\xi = (\xi_1, \xi_2, \dots)$ of independent and identically distributed \mathbb{N}_0 -valued random variables with distribution $\mathbb{P}(\xi_1 = 0) := 1 - |x|$ and $\mathbb{P}(\xi_1 = r) = x_r$, $r \in \mathbb{N}$. Furthermore, for $i, j \in \mathbb{N}$ with $i < j$ let z_{ij} be the sequence (z_1, z_2, \dots) with $z_i = z_j := 1$ and $z_k := 0$ for $k \notin \{i, j\}$. Take a Poisson process on $[0, \infty) \times \mathbb{N}_0^{\mathbb{N}}$ with intensity measure $\lambda \otimes \mu$, where λ denotes Lebesgue measure on $[0, \infty)$ and

$$\mu(A) := \Xi(\{0\}) \sum_{\substack{i, j \in \mathbb{N} \\ i < j}} 1_{\{z_{ij} \in A\}} + \int_{\Delta} P_x(A) \nu(dx) \quad (2)$$

for all measurable $A \subseteq \mathbb{N}_0^{\mathbb{N}}$. Each atom (t, x) corresponds to a reproduction event which is defined as follows. For $r \in \mathbb{N}$ define $J_r := \{j \in \mathbb{N} : \xi_j = r\}$. For $r \in \mathbb{N}$ and $j \in J_r$, the individual (t, j) is a child of the individual $(t-, \min J_r)$. The other lineages are shifted upwards keeping the order they had before the reproduction event. The construction of this countable infinite population model is called the lookdown construction.

We are now able to define the fixation line. Fix $i \in \mathbb{N}$. The levels of the offspring at time $t \geq 0$ of the individual $(0, i + 1)$, that is the individual at time 0 at level $i + 1$, form a subset of \mathbb{N} , whose minimal element (if it exists) we denote by $L_t^{(i)} + 1$. If this subset is empty, we define $L_t^{(i)} := \infty$. For example, if $J_1 = \mathbb{N}$ and $J_r = \emptyset$ for all $r \in \mathbb{N} \setminus \{1\}$, then the individual at time 0 at level 2 has no offspring at all, so in this case we have $L_t^{(1)} = \infty$. By construction, the process $L^{(i)} := (L_t^{(i)})_{t \geq 0}$ has state space $\{i, i + 1, \dots\} \cup \{\infty\}$ and non-decreasing paths. Moreover, $L_t^{(1)} \leq L_t^{(2)} \leq \dots$. We define $L_t := L_t^{(1)}$ and $L := (L_t)_{t \geq 0}$. When L_t reaches level n , all the individuals at time t with levels $1, \dots, n$ are offspring of the single individual $(0, 1)$, an event called fixation in population genetics. The process L is hence called the fixation line. This process can be traced back to Pfaffelhuber and Wakolbinger [22] for the Kingman coalescent. For the Λ -coalescent the fixation line appears in Labbé [15] and was further studied by Hénard [8, 9].

We close the introduction by a brief summary of the organization of the article. Section 2 contains the main results. Propositions 2.1 and 2.2 provide formulas for the infinitesimal rates and the total rates of the block counting process $N = (N_t)_{t \geq 0}$ and the fixation line $L = (L_t)_{t \geq 0}$ for arbitrary Ξ -coalescents. Theorem 2.3 shows that the block counting process N is Siegmund dual to the fixation line L . For Ξ -coalescents with dust, Theorem 2.4 provides a convergence result for N and L when their initial state tends to infinity. The limiting processes are related to the frequencies of singletons of the coalescent. In Sections 3 and 4 we study the Dirichlet coalescent and the Poisson–Dirichlet coalescent respectively. The proofs of the results stated in Section 2 are provided in Section 5. The appendix deals with a duality relation for generalized Stirling numbers being closely related to the Siegmund duality of N and L .

2 Results

Throughout the article we shall use the following subsets of the infinite simplex Δ defined in (1). For $n \in \mathbb{N}$ define $\Delta_n := \{x = (x_r)_{r \in \mathbb{N}} \in \Delta : x_1 + \dots + x_n = 1\}$. Furthermore let $\Delta_f := \bigcup_{n \in \mathbb{N}} \Delta_n = \{x = (x_r)_{r \in \mathbb{N}} \in \Delta : x_1 + \dots + x_n = 1 \text{ for some } n \in \mathbb{N}\}$ and $\Delta^* := \{x \in \Delta : |x| = 1\}$. Note that $\Delta_1 \subset \Delta_2 \subset \dots \subset \Delta_f \subset \Delta^* \subset \Delta$ and that $\nu(\Delta_n) \leq n \Xi(\Delta_n) < \infty$, since $(x, x) = \sum_{r=1}^n x_r^2 = 1/n + \sum_{r=1}^n (x_r - 1/n)^2 \geq 1/n$ for all $n \in \mathbb{N}$ and $x \in \Delta_n$.

In order to state our first result it is convenient to introduce the following urn model which is essentially a version of Kingman's paintbox construction [12, Section 8]. Fix $x = (x_r)_{r \in \mathbb{N}} \in \Delta$. Recall that $|x| := \sum_{i=1}^{\infty} x_i$ and define $x_0 := 1 - |x|$ for convenience. Imagine a countable infinite number of boxes having labels $r \in \mathbb{N}_0$. Balls are allocated successively to these boxes where it is assumed that every ball will go to box $r \in \mathbb{N}_0$ with probability x_r independently of the other balls. If $X_r(i, x)$ denotes the number of balls in box $r \in \mathbb{N}_0$

after $i \in \mathbb{N}_0$ balls have been allocated, then clearly $(X_0(i, x), X_1(i, x), X_2(i, x), \dots)$ has an infinite multinomial distribution with parameters i and (x_0, x_1, x_2, \dots) . The random variable

$$Y(i, x) := X_0(i, x) + \sum_{r=1}^{\infty} 1_{\{X_r(i, x) \geq 1\}} \quad (3)$$

counts the balls contained in box 0 plus the number of other boxes which are non-empty. In the language of Kingman's paintbox, when a ball goes to box $r \in \mathbb{N}$, it will be painted with color r . The box 0 plays a distinguished role. Each ball going to box 0 is painted with a new color never seen before. $Y(i, x)$ is the number of different colors after i balls have been painted.

Proposition 2.1 and 2.2 below underline the well known fact that the process $(Y(i, x))_{i \in \mathbb{N}_0}$ plays a fundamental role in coalescent theory. Proposition 2.1 concerns the infinitesimal rates of block counting process N . These rates are essentially known from the literature (see, for example, [5]). We state the result for the record and since the case $\Xi(\Delta_f) > 0$ requires some attention.

Proposition 2.1 (Rates of the block counting process) *Let Ξ be a finite measure on Δ and let Π be a Ξ -coalescent. The block counting process $N = (N_t)_{t \geq 0}$ of Π moves from state $i \in \mathbb{N}$ to state $j \in \mathbb{N}$ with $j < i$ at the rate*

$$q_{ij} = \Xi(\{0\}) \binom{i}{2} \delta_{j, i-1} + \int_{\Delta} \mathbb{P}(Y(i, x) = j) \nu(dx) \quad (4)$$

with $Y(i, x)$ defined via (3). The probability below the integral in (4) can be provided explicitly as $\mathbb{P}(Y(i, x) = j) = \sum_{k=1}^j f_{ijk}(x)$, where

$$f_{ijk}(x) := \frac{x_0^{j-k}}{(j-k)!} \sum_{\substack{i_1, \dots, i_k \in \mathbb{N} \\ i_1 + \dots + i_k = i-j+k}} \frac{i!}{i_1! \dots i_k!} \sum_{\substack{r_1, \dots, r_k \in \mathbb{N} \\ r_1 < \dots < r_k}} x_{r_1}^{i_1} \dots x_{r_k}^{i_k}. \quad (5)$$

The total rates are

$$\begin{aligned} q_i &:= \sum_{j=1}^{i-1} q_{ij} = \Xi(\{0\}) \binom{i}{2} + \int_{\Delta} \mathbb{P}(Y(i, x) < i) \nu(dx) \\ &= \Xi(\{0\}) \binom{i}{2} + \int_{\Delta} \left(1 - x_0^i - \sum_{k=1}^i \binom{i}{k} x_0^{i-k} \sum_{\substack{r_1, \dots, r_k \in \mathbb{N} \\ \text{all distinct}}} x_{r_1} \dots x_{r_k} \right) \nu(dx), \quad i \in \mathbb{N}. \end{aligned} \quad (6)$$

Moreover, $q_{\infty j} = \nu(\Delta_j) - \nu(\Delta_{j-1})$ for all $j \in \mathbb{N}$ ($\Delta_0 := \emptyset$) and $q_{\infty \infty} = -\nu(\Delta_f)$.

Remarks.

1. From $q_{i+1} - q_i = i\Xi(\{0\}) + \int_{\Delta} \mathbb{P}(Y(i+1, x) = i, Y(i, x) = i) \nu(dx) \geq 0$ we conclude that $q_{i+1} \geq q_i$ with equality $q_{i+1} = q_i$ if and only if $\Xi(\Delta \setminus \Delta_{i-1}) = 0$, $i \in \mathbb{N}$. Thus, if $\Xi(\Delta \setminus \Delta_f) > 0$ then the total rates q_i , $i \in \mathbb{N}$, are pairwise distinct.
2. For the rates of the block counting process of the Dirichlet coalescent and the Poisson-Dirichlet coalescent we refer the reader to (14), (15) and (20).
3. For the Λ -coalescent the rate (4) reduces to the well known formula (see, for example, [23] or [17, Eq. (13)])

$$q_{ij} = \binom{i}{j-1} \int_{[0,1]} x^{i-j-1} (1-x)^{j-1} \Lambda(dx), \quad i, j \in \mathbb{N}, j < i, \quad (7)$$

and the total rates are [17, Eq. (14)]

$$q_i = \Lambda(\{0\}) \binom{i}{2} + \int_{(0,1]} \frac{1 - (1-x)^i - ix(1-x)^{i-1}}{x^2} \Lambda(dx), \quad i \in \mathbb{N}.$$

For the $\beta(a, b)$ -coalescent with parameters $a, b \in (0, \infty)$ the rate (7) reduces to

$$q_{ij} = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \frac{\Gamma(i+1)}{\Gamma(i-2+a+b)} \frac{\Gamma(j-1+b)}{\Gamma(j)} \frac{\Gamma(i-j-1+a)}{\Gamma(i-j+2)}, \quad i, j \in \mathbb{N}, j < i. \quad (8)$$

We now state the analog result for the rates of the fixation line $L = (L_t)_{t \geq 0}$.

Proposition 2.2 (Rates of the fixation line) *Let Ξ be a finite measure on Δ . The fixation line $L = (L_t)_{t \geq 0}$ moves from state $i \in \mathbb{N}$ to state $j \in \mathbb{N}$ with $j > i$ at the rate*

$$\gamma_{ij} = \Xi(\{0\}) \binom{j}{2} \delta_{j, i+1} + \int_{\Delta} \mathbb{P}(Y(j, x) = i, Y(j+1, x) = i+1) \nu(dx) \quad (9)$$

with $Y(\cdot, x)$ defined in (3). Moreover, $\gamma_{i\infty} = \nu(\Delta_i)$ for all $i \in \mathbb{N}$ and $\gamma_{\infty\infty} = 0$. The probability below the integral in (9) can be provided explicitly, namely $\mathbb{P}(Y(j, x) = i, Y(j+1, x) = i+1) = \sum_{k=1}^i g_{ijk}(x)$, where

$$g_{ijk}(x) := \frac{x_0^{i-k}}{(i-k)!} \sum_{\substack{i_1, \dots, i_k \in \mathbb{N} \\ i_1 + \dots + i_k = j-i+k}} \frac{j!}{i_1! \dots i_k!} \sum_{\substack{r_1, \dots, r_k \in \mathbb{N} \\ r_1 < \dots < r_k}} x_{r_1}^{i_1} \dots x_{r_k}^{i_k} \left(1 - \sum_{l=1}^k x_{r_l}\right). \quad (10)$$

The total rates are $\gamma_i := \sum_{j \in \{i+1, i+2, \dots\} \cup \{\infty\}} \gamma_{ij} = q_{i+1}$, $i \in \mathbb{N}$.

Remarks.

1. In general $g_{ijk}(x)$ is not equal to $f_{jik}(x)$ (see (5)) because of the additional factor $1 - \sum_{l=1}^k x_{r_l}$ occurring on the right hand side in (10). This additional factor comes from the fact that in the paintbox construction, on the event that box 0 contains $i-k$ balls and that the boxes r_1, \dots, r_k are non-empty, $\{Y(j+1, x) = i+1\}$ corresponds to the event that ball $j+1$ belongs to a box $r \in \mathbb{N}_0 \setminus \{r_1, \dots, r_k\}$, which has probability $1 - \sum_{l=1}^k x_{r_l}$.
2. Note that $\gamma_{i+1} = \gamma_i$ if and only if $\Xi(\Delta \setminus \Delta_i) = 0$, $i \in \mathbb{N}$. If $\Xi(\Delta \setminus \Delta_f) > 0$ then the total rates γ_i , $i \in \mathbb{N}$, are pairwise distinct.
3. For the Λ -coalescent the rate (9) reduces to

$$\gamma_{ij} = \binom{j}{i-1} \int_{[0,1]} x^{j-i-1} (1-x)^i \Lambda(dx), \quad i, j \in \mathbb{N}, i < j, \quad (11)$$

in agreement with [9, Lemma 2.3]. The total rates are

$$\gamma_i = q_{i+1} = \Lambda(\{0\}) \binom{i+1}{2} + \int_{(0,1]} \frac{1 - (1+ix)(1-x)^i}{x^2} \Lambda(dx), \quad i \in \mathbb{N}.$$

For the Λ -coalescent the equality $\gamma_i = q_{i+1}$ was already observed by Hénard [9].

For the Kingman coalescent ($\Lambda = \delta_0$) we have $\gamma_i = \gamma_{i, i+1} = \binom{i+1}{2}$ and $\gamma_{ij} = 0$ for all $j \notin \{i, i+1\}$. Thus, L is a pure birth process with state space $\mathbb{N} \cup \{\infty\}$ and birth rates $\gamma_i = \binom{i+1}{2}$, $i \in \mathbb{N}$. This process explodes, i.e. $\mathbb{P}(L_t = \infty) > 0$ for all $t > 0$, since $\sum_{i=1}^{\infty} 1/\gamma_i < \infty$. In fact, L reaches ∞ in finite time almost surely. For more details on explosion of L we refer the reader to Remark 3 after Theorem 2.3.

For the $\beta(a, b)$ -coalescent with $a, b \in (0, \infty)$ the rates (11) of the fixation line process reduce to

$$\gamma_{ij} = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \frac{\Gamma(i+b)}{\Gamma(i)} \frac{\Gamma(j+1)}{\Gamma(j-1+a+b)} \frac{\Gamma(j-i-1+a)}{\Gamma(j-i+2)}, \quad i, j \in \mathbb{N}, i < j. \quad (12)$$

Simple formulas for the total rates γ_i seem to be only available for particular parameter choices of a and b . For example, for the $\beta(2 - \alpha, \alpha)$ -coalescent with parameter $0 < \alpha < 2$, which has attracted the interest of several researchers, the fixation line has total rates

$$\begin{aligned}\gamma_i &= \sum_{j=i+1}^{\infty} \gamma_{ij} = \frac{1}{\Gamma(2 - \alpha)\Gamma(\alpha)} \frac{\Gamma(i + \alpha)}{\Gamma(i)} \sum_{j=i+1}^{\infty} \frac{\Gamma(j - i + 1 - \alpha)}{\Gamma(j - i + 2)} \\ &= \frac{1}{\Gamma(2 - \alpha)\Gamma(\alpha)} \frac{\Gamma(i + \alpha)}{\Gamma(i)} \frac{\Gamma(2 - \alpha)}{\alpha} = \frac{\Gamma(i + \alpha)}{\Gamma(\alpha + 1)\Gamma(i)} = \prod_{k=1}^{i-1} \frac{k + \alpha}{k}, \quad i \in \mathbb{N}.\end{aligned}$$

In particular, $\gamma_i = i$ for the Bolthausen–Sznitman coalescent ($\alpha = 1$). Another class of beta-coalescents for which a nice formula for the total rate γ_i is available is the $\beta(3, b)$ -coalescent with parameter $b > 0$. In this case the fixation line process has total rates

$$\begin{aligned}\gamma_i &= \sum_{j=i+1}^{\infty} \gamma_{ij} = \frac{\Gamma(3 + b)}{\Gamma(3)\Gamma(b)} \frac{\Gamma(i + b)}{\Gamma(i)} \sum_{j=i+1}^{\infty} \frac{\Gamma(j + 1)}{\Gamma(j + b + 2)} \\ &= \frac{\Gamma(3 + b)}{\Gamma(3)\Gamma(b)} \frac{\Gamma(i + b)}{\Gamma(i)} \frac{\Gamma(i + 2)}{b\Gamma(i + b + 2)} \\ &= \frac{(b + 1)(b + 2)}{2} \frac{i(i + 1)}{(i + b)(i + b + 1)}, \quad i \in \mathbb{N}.\end{aligned}$$

We now turn to the duality of the block counting process N and the fixation line L . The following result (Theorem 2.3) is a reformulation and generalization of Lemma 2.1 of Hénard [9]. Note that Theorem 2.3 holds for any Ξ -coalescent. Recall the notation $S := \mathbb{N} \cup \{\infty\}$.

Theorem 2.3 (Siegmund duality of N and L) *Let Π be a Ξ -coalescent and let $N = (N_t)_{t \geq 0}$ and $L = (L_t)_{t \geq 0}$ denote the block counting process and the fixation line of Π respectively. Then N is dual (in the sense of Liggett [16, p. 84, Definition 3.1]) to L with respect to the Siegmund duality kernel $H : S^2 \rightarrow \{0, 1\}$ defined via $H(i, j) := 1$ for $i \leq j$ and $H(i, j) := 0$ otherwise, i.e.*

$$\begin{aligned}\mathbb{P}(N_t^{(i)} \leq j) &= \mathbb{P}(N_t \leq j \mid N_0 = i) = \mathbb{E}(H(N_t, j) \mid N_0 = i) \\ &= \mathbb{E}(H(i, L_t) \mid L_0 = j) = \mathbb{P}(L_t \geq i \mid L_0 = j) = \mathbb{P}(L_t^{(j)} \geq i)\end{aligned}$$

for all $i, j \in S$ and all $t \geq 0$. If $Q = (q_{ij})_{i, j \in S}$ and $\Gamma = (\gamma_{ij})_{i, j \in S}$ denote the generator matrices of N and L respectively then $q_{i, \leq j} := \sum_{k \in S, k \leq j} q_{ik} = \sum_{k \in S, k \geq i} \gamma_{jk} =: \gamma_{j, \geq i}$ for all $i, j \in S$.

Remarks.

1. Note that L is dual to N with respect to the transposed duality kernel $H^\top : S^2 \rightarrow \{0, 1\}$ defined via $H^\top(i, j) := H(j, i)$ for all $i, j \in S$. Let $\tilde{S} := S \setminus \{1, \infty\} = \mathbb{N} \setminus \{1\}$ denote the set of states which are transient for N and L . Define the matrix $\tilde{H} := (H(i, j))_{i, j \in \tilde{S}}$. The matrix inverse \tilde{H}^{-1} of \tilde{H} has entries

$$\tilde{H}^{-1}(i, j) = \begin{cases} 1 & \text{if } j = i, \\ -1 & \text{if } j = i + 1, \\ 0 & \text{otherwise.} \end{cases}$$

For $i, j \in \tilde{S}$ define $g_{ij} := \int_0^\infty \mathbb{P}(N_t^{(i)} = j) dt$ and $\hat{g}_{ij} := \int_0^\infty \mathbb{P}(L_t^{(i)} = j) dt$, and let $G = (g_{ij})_{i, j \in \tilde{S}}$ and $\hat{G} = (\hat{g}_{ij})_{i, j \in \tilde{S}}$ denote the Green matrices of N and L respectively (see, for example, Norris [21, p. 145]).

From Theorem 2.3 it follows that $G\tilde{H} = \tilde{H}\widehat{G}^\top$. Thus, G can be computed from \widehat{G} and vice versa via $G = \tilde{H}\widehat{G}^\top\tilde{H}^{-1}$ and $\widehat{G} = (\tilde{H}^{-1}G\tilde{H})^\top$, i.e.

$$g_{i2} = \sum_{\substack{k \in \tilde{S} \\ k \geq i}} \widehat{g}_{2k}, \quad g_{ij} = \sum_{\substack{k \in \tilde{S} \\ k \geq i}} (\widehat{g}_{jk} - \widehat{g}_{j-1,k}), \quad i \in \tilde{S}, j \in \tilde{S} \setminus \{2\}$$

and

$$\widehat{g}_{ij} = \sum_{\substack{k \in \tilde{S} \\ k \leq i}} (g_{jk} - g_{j+1,k}), \quad i, j \in \tilde{S}.$$

2. As in [29] we say that Π comes down from infinity if $\mathbb{P}(N_t < \infty) = 1$ for all $t > 0$. We say that Π stays infinite if $\mathbb{P}(N_t = \infty) = 1$ for all $t > 0$. Note that there exist coalescents, for example the Dirichlet coalescent studied in Section 3, that neither come down from infinity nor stay infinite. We refer the reader to [28, 29] and [10] for methods to determine whether a coalescent Π comes down from infinity or stays infinite.
3. We say that L does not explode if $T_\infty := \inf\{t > 0 : L_{t-} = \infty\} = \infty$ almost surely. Note that L does not explode if and only if $\mathbb{P}(L_t < \infty) = 1$ for all $t \geq 0$. By the general explosion criterion for Markov chains, L does not explode if and only if $\sum_{n=0}^{\infty} 1/\gamma_{\chi_n} = \infty$ almost surely, where $\chi = (\chi_n)_{n \in \mathbb{N}_0}$ denotes the jump chain of L . Note that χ has transition probabilities $p_{ij} := \gamma_{ij}/\gamma_i$, $1 \leq i < j \leq \infty$.
4. If Π comes down from infinity then L explodes. Moreover, Π stays infinite if and only if L does not explode.

Proof. If Π comes down from infinity, then Π eventually becomes absorbed almost surely, i.e. $\lim_{t \rightarrow \infty} \mathbb{P}(N_t = 1) = 1$. Thus, by duality, $\mathbb{P}(L_t = \infty) = \mathbb{P}(N_t = 1) > 0$ for all sufficiently large t , i.e. L explodes.

If Π stays infinite, then $\mathbb{P}(N_t = \infty) = 1$ for all $t \geq 0$. Thus, $\mathbb{P}(L_t = \infty) = \mathbb{P}(N_t = 1) = 0$ for all $t \geq 0$, i.e. L does not explode. Conversely, suppose that L does not explode. Then, by the first statement, Π does not come down from infinity. Moreover, we must have $\gamma_{i\infty} = 0$ for all $i \in \mathbb{N}$, because otherwise every L_t would be equal to ∞ with positive probability. Since $\gamma_{i\infty} = \nu(\Delta_i)$ it follows that $\nu(\Delta_f) = \lim_{i \rightarrow \infty} \nu(\Delta_i) = 0$. Thus, $\Xi(\Delta_f) = 0$. But under the additional assumption that $\Xi(\Delta_f) = 0$ the coalescent does not come down from infinity if and only if the coalescent stays infinite (see [29]).

5. Recall that L explodes if Π comes down from infinity. The converse holds under the additional assumption that $\Xi(\Delta_f) = 0$, but it does not hold in general. Examples where L explodes but Π does not come down from infinity are provided in Section 3 (Dirichlet coalescent).

A Ξ -coalescent $\Pi = (\Pi_t)_{t \geq 0}$ has proper frequencies if, for all times $t \geq 0$, the frequency of singletons S_t of Π_t satisfies $S_t = 0$ almost surely. For a precise definition of S_t we refer the reader to [18, Section 3]. Schweinsberg [29, Proposition 30] showed that Π does not have proper frequencies if and only if $\Xi(\{0\}) = 0$ and $\int_{\Delta} |x| \nu(dx) < \infty$. In this case the process $Z := (Z_t)_{t \geq 0} := (-\log S_t)_{t \geq 0}$ (with the convention $-\log 0 := \infty$) is a drift-free subordinator with state space $[0, \infty]$ and Laplace exponent

$$\Phi(\eta) = \int_{\Delta} (1 - (1 - |x|)^\eta) \nu(dx), \quad \eta \geq 0. \quad (13)$$

Note that $\mathbb{E}(S_t^\eta) = \mathbb{E}(e^{-\eta Z_t}) = e^{-t\Phi(\eta)}$, $\eta \geq 0$. A coalescent without proper frequencies is also called a coalescent with dust component [6]. Theorem 2.4 below clarifies the asymptotic behavior of the block counting process $N^{(n)}$ and the fixation line $L^{(n)}$ as $n \rightarrow \infty$ for Ξ -coalescents with dust. Note that we use the conventions $e^{-\infty} := 0$, $e^\infty := \infty$ and $1/0 := \infty$.

Theorem 2.4 *Let Ξ be a Ξ -coalescent with dust, i.e. $\Xi(\{0\}) = 0$ and $\int_{\Delta} |x| \nu(dx) < \infty$. Then, the following two assertions hold.*

- a) *As $n \rightarrow \infty$ the scaled block counting process $(N_t^{(n)}/n)_{t \geq 0}$ converges in $D_{[0,1]}[0, \infty)$ to the frequency of singleton process $S = (S_t)_{t \geq 0} = (e^{-Z_t})_{t \geq 0}$.*
- b) *As $n \rightarrow \infty$ the scaled fixation line process $(L_t^{(n)}/n)_{t \geq 0}$ converges in $D_{[1,\infty]}[0, \infty)$ to the inverse frequency of singleton process $(1/S_t)_{t \geq 0} = (e^{Z_t})_{t \geq 0}$.*

Remarks.

1. Theorem 2.4 can be stated logarithmically as follows. For Ξ -coalescents with dust, as $n \rightarrow \infty$, both processes $(\log n - \log N_t^{(n)})_{t \geq 0}$ and $(\log L_t^{(n)} - \log n)_{t \geq 0}$ converge in $D_{[0,\infty]}[0, \infty)$ to the drift-free subordinator Z with Laplace exponent (13). Clearly, Theorem 2.4 holds for Λ -coalescents with dust, for example for $\beta(a, b)$ -coalescents with $a > 1$ and $b > 0$.
2. If Ξ is concentrated on Δ^* then the coalescent has dust if and only if ν is finite. In this case the Laplace exponent (13) satisfies $\Phi(\eta) = \nu(\Delta^*)$, $\eta > 0$, so S_t has the same distribution as $1_{\{T_f > t\}}$ for all $t \geq 0$, where T_f is exponentially distributed with parameter $\nu(\Delta^*)$. Examples are the Dirichlet coalescent studied in Section 3, the Poisson–Dirichlet coalescent [27, Section 3] and the two-parameter Poisson–Dirichlet coalescent [18, Section 6]. More information on the two-parameter Poisson–Dirichlet coalescent is provided in Section 4.
3. Theorem 2.4 excludes dust-free coalescents. For the Bolthausen–Sznitman coalescent we refer the reader to [14], [19] and [30] for asymptotic results concerning the block counting process $N^{(n)}$ and the fixation line $L^{(n)}$. For dust-free coalescents different from the Bolthausen–Sznitman coalescent we leave the asymptotic analysis of $N^{(n)}$ and $L^{(n)}$ for future work.

3 The Dirichlet coalescent

Let $X := (X_1, \dots, X_N)$ be symmetric Dirichlet distributed with parameters $N \in \mathbb{N}$ and $\alpha > 0$ and let $X_{(1)} \geq \dots \geq X_{(N)}$ denote the order statistics of X . We consider the Ξ -coalescent when the characteristic measure ν is the distribution of $(X_{(1)}, \dots, X_{(N)}, 0, 0, \dots)$. We call this coalescent the Dirichlet coalescent with parameters $N \in \mathbb{N}$ and $\alpha > 0$. Note that ν is concentrated on Δ_N . The Dirichlet coalescent neither comes down from infinity nor stays infinite. More precisely, using the notation A_f and T_f from [29], $\mathbb{P}(N_t = \infty) = \mathbb{P}(T_f > t) = e^{-t}$ for all $t \geq 0$, since (see [29, Lemma 41]) T_f is exponentially distributed with parameter $\int_{\Delta} P_x(A_f) \nu(dx) = \int_{\Delta_f} P_x(A_f) \nu(dx) = \nu(\Delta_f) = 1$. Note that the fixation line $L = (L_t)_{t \geq 0}$ explodes, since the coalescent does not stay infinite.

In agreement with [11] we use the notation $[x|y]_n := \prod_{k=0}^{n-1} (x+ky)$ and $(x|y)_n := \prod_{k=0}^{n-1} (x-ky)$ for $x, y \in \mathbb{R}$ and $n \in \mathbb{N}_0$ with the convention that empty products are equal to 1. We furthermore write $[x]_n := [x|1]_n$ and $(x)_n := (x|1)_n$. The proof of the following lemma is given at the end of this section.

Lemma 3.1 (Rates of the block counting process) *The block counting process of the Dirichlet coalescent with parameters $N \in \mathbb{N}$ and $\alpha > 0$ has infinitesimal rates*

$$q_{ij} = \frac{(N\alpha|\alpha)_j}{[N\alpha]_i} S_{\alpha}(i, j) \quad 1 \leq j < i, \quad (14)$$

where the $S_{\alpha}(i, j) := S(i, j; -1, \alpha, 0)$ are the generalized Stirling numbers defined in [11]

satisfying the recursion $S_\alpha(i+1, j) = S_\alpha(i, j-1) + (i + \alpha j)S_\alpha(i, j)$. Alternatively,

$$q_{ij} = \frac{\binom{N}{j}}{\binom{N\alpha + i - 1}{i}} \sum_{\substack{i_1, \dots, i_j \in \mathbb{N} \\ i_1 + \dots + i_j = i}} \binom{i_1 + \alpha - 1}{i_1} \dots \binom{i_j + \alpha - 1}{i_j}, \quad 1 \leq j < i. \quad (15)$$

Remarks.

1. The Dirichlet coalescent is closely related to the Chinese restaurant process [24]. Imagine a restaurant with $N \in \mathbb{N}$ tables each of infinite capacity. Customers enter successively the restaurant. When the $(i + 1)$ th customer arrives and j tables are already occupied (by at least one person), the customer sits at an empty table with probability $(N\alpha - j\alpha)/(N\alpha + i)$. This corresponds to Pitman's [24] Chinese restaurant process with $\kappa := \alpha$ and $\theta := N\alpha$. Let K_i denote the number of occupied tables after the i th customer has been seated. It is easily verified by induction on i that K_i has distribution $\mathbb{P}(K_i = j) = (N\alpha|_\alpha)_j S_\alpha(i, j)/[N\alpha]_i$, $j \in \{1, \dots, i\}$. Note that K_i has mean

$$\mathbb{E}(K_i) = N - N \frac{[(N-1)\alpha]_i}{[N\alpha]_i}.$$

2. The Dirichlet coalescent has total rates $q_i := \sum_{j=1}^{i-1} q_{ij} = \sum_{j=1}^{i-1} \mathbb{P}(K_i = j) = 1 - \mathbb{P}(K_i = i) = 1 - (N\alpha|_\alpha)_i/[N\alpha]_i$. Note that $0 = q_1 < q_2 < \dots < q_N < 1 = q_{N+1} = q_{N+2} = \dots$. The Dirichlet coalescent therefore serves as an example showing that in general the total rates of a coalescent do not need to be pairwise distinct.

Examples.

1. For $\alpha = 1$ the Stirling number $S_1(i, j)$ is the Lah number $S(i, j; -1, 1, 0) = \frac{i!}{j!} \binom{i-1}{j-1}$ and we conclude that $q_{ij} = \binom{N}{j} \binom{i-1}{j-1} / \binom{N+i-1}{i}$. In this case K_i is hypergeometric distributed with parameters $N + i - 1$, N and i . The total rates are $q_i = 1 - N!(N - 1)!/(N - i)!/(N + i - 1)!$ for $i \leq N$ and $q_i = 1$ for $i > N$.
2. For $\alpha \rightarrow \infty$ it follows that $q_{ij} = N^{-i} (N)_j S(i, j)$, where the $S(i, j)$ are the usual Stirling numbers of the second kind. In this case K_i counts the number of non-empty boxes when i balls are allocated at random to N boxes. This corresponds to the Dirac Ξ -coalescent where the measure ν assigns its total mass 1 to the single point $x \in \Delta$ whose first N coordinates are all equal to $1/N$.
3. For $\alpha \rightarrow 0$ and $N \rightarrow \infty$ such that $N\alpha \rightarrow \theta \in (0, \infty)$ the rates q_{ij} converge to those of the Poisson-Dirichlet coalescent with parameter θ and $\alpha = 0$ studied in the following Section 4.

In the following we provide the asymptotics of some functionals of the Dirichlet n -coalescent when the sample size n tends to infinity. By Theorem 2.4 and Remark 3 thereafter, $(N_t^{(n)}/n)_{t \geq 0}$ converges in $D_{[0,1]}[0, \infty)$ to $(S_t)_{t \geq 0}$ as $n \rightarrow \infty$ and $(L_t^{(n)}/n)_{t \geq 0}$ converges in $D_{[1, \infty]}[0, \infty)$ to $(1/S_t)_{t \geq 0}$, where $S_t := 1_{\{T_f > t\}}$ and T_f is exponentially distributed with parameter 1.

Let C_n denote the number of jumps and $\tau_n := \inf\{t > 0 : N_t = 1\}$ denote the absorption time of the Dirichlet n -coalescent. The following lemma clarifies the asymptotics of C_n and τ_n as $n \rightarrow \infty$. Its proof is given at the end of this section.

Lemma 3.2 (Asymptotics of the number of jumps and the absorption time)

For the Dirichlet coalescent with parameter $N \in \mathbb{N}$ and $\alpha > 0$ the following two statements hold.

- (i) The number of jumps C_n converges to $C_\infty := 1 + C_N$ in distribution as $n \rightarrow \infty$. The limit C_∞ has distribution $\mathbb{P}(C_\infty = k) = r_{N1}^{(k-1)}$, $1 \leq k \leq N$, and $r_{ij} := q_{ij}/q_i$, $1 \leq j < i$, denote the transition probabilities of the jump chain of the block counting process.

(ii) The absorption time τ_n converges to $\tau_\infty := E + \tau_N$ in distribution as $n \rightarrow \infty$, where E is standard exponentially distributed and independent of τ_N .

We now turn to the fixation line $L = (L_t)_{t \geq 0}$ of the Dirichlet coalescent.

Lemma 3.3 (Rates of the fixation line) *The fixation line of the Dirichlet coalescent with parameters $N \in \mathbb{N}$ and $\alpha > 0$ has rates*

$$\gamma_{ij} = \frac{(N\alpha|\alpha)_{i+1}}{[N\alpha]_{j+1}} S_\alpha(j, i), \quad i, j \in \mathbb{N}, i < j. \quad (16)$$

Moreover $\gamma_{i\infty} = 0$ for $i \in \{1, \dots, N-1\}$ and $\gamma_{i\infty} = 1$ for $i \in \{N, N+1, \dots\}$.

Remark. Note that $\gamma_{ij} = \frac{N\alpha-i\alpha}{N\alpha+j} q_{ji} = \mathbb{P}(K_j = i, K_{j+1} = i+1) = \mathbb{P}(K_j \leq i, K_{j+1} > i) = \mathbb{P}(K_j \leq i) - \mathbb{P}(K_{j+1} \leq i)$. Summation over all $j \in \{i+1, i+2, \dots\} \cup \{\infty\}$ shows that the fixation line has total rates $\gamma_i = q_{i+1}$, $i \in \mathbb{N}$, in agreement with Proposition 2.2.

Example. For $\alpha = 1$ we obtain

$$\gamma_{ij} = \frac{N-i}{N+j} q_{ji} = \binom{N-1}{i} \binom{j-1}{j-i} / \binom{N+j}{N}.$$

By duality (Theorem 2.3), for all $i, j \in \mathbb{N}$ with $i > j$, the two quantities

$$q_{i, \leq j} = \sum_{k=1}^j q_{ik} = \frac{1}{[N\alpha]_i} \sum_{k=1}^j (N\alpha|\alpha)_j S_\alpha(i, j) \quad (17)$$

and

$$\gamma_{j, \geq i} = \sum_{\substack{k \in \mathbb{N} \cup \{\infty\} \\ k \geq i}} \gamma_{jk} = \begin{cases} (N\alpha|\alpha)_{j+1} \sum_{k=i}^{\infty} \frac{S_\alpha(k, j)}{[N\alpha]_{k+1}} & \text{if } j < N \\ \gamma_{j\infty} = 1 & \text{if } j \geq N \end{cases} \quad (18)$$

coincide. The equality of (17) and (18) follows alternatively from [20, Lemma 4.1], applied to the Markov chain K , or from Lemma 6.1 in the appendix, applied with $a := -1$, $b := \alpha$, $r := 0$ and $t := N\alpha$. Note that $\lim_{i \rightarrow \infty} q_{i, \leq j} = \lim_{i \rightarrow \infty} \mathbb{P}(K_i \leq j) = 0$ for all $j < N$, since all states $j < N$ of the Markov chain K are transient.

In the remaining part of this section we prove Lemma 3.1, Lemma 3.2 and Lemma 3.3.

Proof. (of Lemma 3.1) Since the measure ν is concentrated on Δ_N it follows from (4) and (5) that

$$q_{ij} = \frac{i!}{j!} \sum_{\substack{i_1, \dots, i_j \in \mathbb{N} \\ i_1 + \dots + i_j = i}} \frac{\phi(i_1, \dots, i_j)}{i_1! \dots i_j!}, \quad (19)$$

where

$$\phi(i_1, \dots, i_j) := \int_{\Delta} \sum_{\substack{r_1, \dots, r_j \in \mathbb{N} \\ \text{all distinct}}} x_{r_1}^{i_1} \dots x_{r_j}^{i_j} \nu(dx) = \int_{\Delta} \sum_{\substack{r_1, \dots, r_j = 1 \\ \text{all distinct}}}^N x_{r_1}^{i_1} \dots x_{r_j}^{i_j} \nu(dx).$$

The function below the latter integral is symmetric with respect to x_1, \dots, x_N . Thus,

$$\phi(i_1, \dots, i_j) = \int \sum_{\substack{r_1, \dots, r_j = 1 \\ \text{all distinct}}}^N x_{r_1}^{i_1} \dots x_{r_j}^{i_j} D_N(\alpha)(dx_1, \dots, dx_N) = (N)_j \mathbb{E}(X_1^{i_1} \dots X_j^{i_j}),$$

where the last equality holds, since the Dirichlet distribution $D_N(\alpha)$ is symmetric and, hence, the integrals over each summand is the same. The moments of the symmetric Dirichlet distribution $D_N(\alpha)$ are well known (see, for example, [13, p. 488]) to be

$\mathbb{E}(X_1^{i_1} \cdots X_j^{i_j}) = [\alpha]_{i_1} \cdots [\alpha]_{i_j} / [N\alpha]_i$, where $i := i_1 + \cdots + i_j$. Plugging all this into (19) leads to

$$\begin{aligned} q_{ij} &= \frac{i!}{j!} \frac{(N)_j}{[N\alpha]_i} \sum_{\substack{i_1, \dots, i_j \in \mathbb{N} \\ i_1 + \cdots + i_j = i}} \frac{[\alpha]_{i_1} \cdots [\alpha]_{i_j}}{i_1! \cdots i_j!} \\ &= \frac{\binom{N}{j}}{\binom{N\alpha + i - 1}{i}} \sum_{\substack{i_1, \dots, i_j \in \mathbb{N} \\ i_1 + \cdots + i_j = i}} \binom{i_1 + \alpha - 1}{i_1} \cdots \binom{i_j + \alpha - 1}{i_j}, \end{aligned}$$

which is (15). Since $(N\alpha|\alpha)_j = (N)_j \alpha^j$ and

$$S_\alpha(i, j) = \frac{i!}{j!} \sum_{\substack{i_1, \dots, i_j \in \mathbb{N} \\ i_1 + \cdots + i_j = i}} \frac{1}{i_1! \cdots i_j!} \frac{\Gamma(\alpha + i_1)}{\Gamma(\alpha + 1)} \cdots \frac{\Gamma(\alpha + i_j)}{\Gamma(\alpha + 1)}$$

it follows that the right hand side of (15) is equal to the right hand side of (14). \square

Proof. (of Lemma 3.2) Clearly, $(C_n)_{n \in \mathbb{N}}$ satisfies the distributional recursion $C_n \stackrel{d}{=} 1 + C_{I_n}$ with initial condition $C_1 = 0$, where I_n denotes the state of the jump chain of the block counting process of the Dirichlet n -coalescent with parameters $N \in \mathbb{N}$ and $\alpha > 0$ after its first jump. By Lemma 3.1 and the remarks thereafter, I_n has distribution

$$\mathbb{P}(I_n = k) = \frac{q_{nk}}{q_n} = \frac{\mathbb{P}(K_n = k)}{1 - \mathbb{P}(K_n = n)}, \quad 1 \leq k < n.$$

Since $K_n \rightarrow N$ in distribution as $n \rightarrow \infty$ we conclude that $I_n \rightarrow N$ in distribution as $n \rightarrow \infty$. Thus, $C_n \stackrel{d}{=} 1 + C_{I_n} \rightarrow 1 + C_N$ in distribution as $n \rightarrow \infty$.

The sequence $(\tau_n)_{n \in \mathbb{N}}$ satisfies the distributional recursion $\tau_n \stackrel{d}{=} E_n + \tau_{I_n}$ with initial condition $\tau_1 = 0$, where E_n is independent of I_n and exponentially distributed with parameter $q_n = 1 - \mathbb{P}(K_n = n)$. Since $q_n \rightarrow 1$ as $n \rightarrow \infty$ and $I_n \rightarrow N$ in distribution as $n \rightarrow \infty$ we conclude that $\tau_n \stackrel{d}{=} E_n + \tau_{I_n} \rightarrow E + \tau_N$ as $n \rightarrow \infty$, where E is standard exponentially distributed and independent of τ_N . \square

Proof. (of Lemma 3.3) Since ν is concentrated on Δ_N it follows from (9) and (10) that

$$\gamma_{ij} = \frac{j!}{i!} \sum_{\substack{j_1, \dots, j_i \in \mathbb{N} \\ j_1 + \cdots + j_i = j}} \frac{\psi(j_1, \dots, j_i)}{j_1! \cdots j_i!},$$

where

$$\psi(j_1, \dots, j_i) := \int_{\Delta} \sum_{\substack{r_1, \dots, r_i = 1 \\ \text{all distinct}}}^N x_{r_1}^{j_1} \cdots x_{r_i}^{j_i} \left(1 - \sum_{k=1}^i x_{r_k} \right) \nu(dx).$$

The same arguments as in the proof of Lemma 3.1 show that

$$\begin{aligned} \psi(j_1, \dots, j_i) &= (N)_i \mathbb{E} \left(X_1^{j_1} \cdots X_i^{j_i} \left(1 - \sum_{k=1}^i X_k \right) \right) \\ &= (N)_i \left(\frac{[\alpha]_{j_1} \cdots [\alpha]_{j_i}}{[N\alpha]_j} - \sum_{k=1}^i \frac{[\alpha]_{j_1} \cdots [\alpha]_{j_k+1} \cdots [\alpha]_{j_i}}{[N\alpha]_{j+1}} \right) \\ &= (N)_i \frac{[\alpha]_{j_1} \cdots [\alpha]_{j_i}}{[N\alpha]_{j+1}} \left((N\alpha + j) - \sum_{k=1}^i (\alpha + j_k) \right) \\ &= \frac{N\alpha - i\alpha}{N\alpha + j} (N)_i \frac{[\alpha]_{j_1} \cdots [\alpha]_{j_i}}{[N\alpha]_j} = \frac{N\alpha - i\alpha}{N\alpha + j} \phi(j_1, \dots, j_i). \end{aligned}$$

It follows that $\gamma_{ij} = q_{ji}(N\alpha - i\alpha)/(N\alpha + j)$ and (16) follows from (14). Moreover, by Proposition 2.2, $\gamma_{i\infty} = \nu(\Delta_i)$ for all $i \in \mathbb{N}$. It remains to note that $\nu(\Delta_i) = 0$ for $i < N$ and $\nu(\Delta_i) = 1$ for $i \geq N$. \square

4 The Poisson–Dirichlet coalescent

If $\Xi(\{0\}) = 0$ and if the measure $\nu(dx) = \Xi_0(dx)/(x, x)$ is the Poisson–Dirichlet distribution with parameters $0 \leq \alpha < 1$ and $\theta > -\alpha$ then the Ξ -coalescent is called the two-parameter Poisson–Dirichlet coalescent [18]. Note that ν is concentrated on $\Delta^* \setminus \Delta_f$. Since $\int_{\Delta} |x| \nu(dx) = \nu(\Delta^*) = 1 < \infty$ it follows that this coalescent has dust and hence cannot come down from infinity. Since $\Xi(\Delta_f) = 0$, this coalescent stays infinite, and, hence, L does not explode. The associated block counting process has rates (see [18, p. 2170])

$$q_{ij} = c_{j,\alpha,\theta} \frac{\Gamma(\theta + \alpha j)}{\Gamma(\theta + i)} s_{\alpha}(i, j), \quad i > j, \quad (20)$$

where

$$c_{j,\alpha,\theta} := \prod_{k=1}^j \frac{\Gamma(\theta + 1 + (k-1)\alpha)}{\Gamma(1-\alpha)\Gamma(\theta + k\alpha)}$$

and

$$s_{\alpha}(i, j) := \frac{i!}{j!} \sum_{\substack{i_1, \dots, i_j \in \mathbb{N} \\ i_1 + \dots + i_j = i}} \frac{\Gamma(i_1 - \alpha) \cdots \Gamma(i_j - \alpha)}{i_1! \cdots i_j!}$$

is a kind of generalized absolute Stirling number of the first kind satisfying the recursion $s_{\alpha}(i+1, j) = \Gamma(1-\alpha)s_{\alpha}(i, j-1) + (i-\alpha j)s_{\alpha}(i, j)$. More precisely, $s_{\alpha}(i, j)/(\Gamma(1-\alpha))^j$ coincides with the generalized Stirling number $S(i, j; -1, -\alpha, 0)$ as defined in Hsu and Shiue [11]. For $\alpha = 0$ (and hence $\theta > 0$) the rate q_{ij} reduces to

$$q_{ij} = \theta^j \frac{\Gamma(\theta)}{\Gamma(\theta + i)} s(i, j), \quad i > j,$$

where the $s(i, j) := S(i, j; -1, 0, 0)$ are the (usual) absolute Stirling numbers of the first kind. For $\theta = 0$ (and hence $0 < \alpha < 1$) we obtain

$$q_{ij} = \frac{\alpha^{j-1}}{(\Gamma(1-\alpha))^j} \frac{(j-1)!}{(i-1)!} s_{\alpha}(i, j) = \alpha^{j-1} \frac{(j-1)!}{(i-1)!} S(i, j; -1, -\alpha, 0), \quad i > j.$$

In order to compute the total rates of the block counting process of the two-parameter Poisson–Dirichlet coalescent we proceed as follows. Let $K = (K_n)_{n \in \mathbb{N}_0}$ be a Markov chain with state space \mathbb{N}_0 , $K_0 := 0$, $K_1 := 1$ and transition probabilities $p_k(n) := \mathbb{P}(K_{n+1} = k+1 | K_n = k) := (\theta + \alpha k)/(\theta + n)$ and $\mathbb{P}(K_{n+1} = k | K_n = k) = 1 - p_k(n)$ for $n \in \mathbb{N}$ and $k \in \{1, \dots, n\}$. Note that $1 \leq K_n \leq n$, $n \in \mathbb{N}$. As for the Dirichlet coalescent one may interpret K_n as the number of occupied tables in a particular Chinese restaurant process. When customer $n+1$ enters the restaurant and k tables are already occupied, he sits at an empty table with probability $p_k(n)$. In the following it is verified by induction on $n \in \mathbb{N}$ that K_n has distribution (see also Pitman [24, p. 65, Eq. (3.11)])

$$\mathbb{P}(K_n = k) = c_{k,\alpha,\theta} \frac{\Gamma(\theta + \alpha k)}{\Gamma(\theta + n)} s_{\alpha}(n, k), \quad k \in \mathbb{N}_0.$$

For $n = 1$ this is obvious, since $K_1 = 1$, $c_{1,\alpha,\theta} = \Gamma(\theta + 1)/\Gamma(1-\alpha)/\Gamma(\theta + \alpha)$ and $s_{\alpha}(1, 1) = \Gamma(1-\alpha)$. The induction step from $n \in \mathbb{N}$ to $n+1$ works as follows. By the Markov property, $\mathbb{P}(K_{n+1} = k) = p_{k-1}(n)\mathbb{P}(K_n = k-1) + (1 - p_k(n))\mathbb{P}(K_n = k)$. By induction,

$$\begin{aligned} p_{k-1}(n)\mathbb{P}(K_n = k-1) &= \frac{\theta + \alpha(k-1)}{\theta + n} c_{k-1,\alpha,\theta} \frac{\Gamma(\theta + \alpha(k-1))}{\Gamma(\theta + n)} s_{\alpha}(n, k-1) \\ &= \frac{\Gamma(\theta + 1 + \alpha(k-1))}{\Gamma(\theta + n + 1)} c_{k-1,\alpha,\theta} s_{\alpha}(n, k-1) \\ &= \frac{\Gamma(\theta + k\alpha)\Gamma(1-\alpha)}{\Gamma(\theta + n + 1)} c_{k,\alpha,\theta} s_{\alpha}(n, k-1) \end{aligned}$$

and

$$\begin{aligned} (1 - p_k(n)) \mathbb{P}(K_n = k) &= \frac{n - \alpha k}{\theta + n} c_{k,\alpha,\theta} \frac{\Gamma(\theta + k\alpha)}{\Gamma(\theta + n)} s_\alpha(n, k) \\ &= \frac{\Gamma(\theta + k\alpha)}{\Gamma(\theta + n + 1)} c_{k,\alpha,\theta} (n - \alpha k) s_\alpha(n, k). \end{aligned}$$

Summation of these two terms yields

$$\begin{aligned} \mathbb{P}(K_{n+1} = k) &= \frac{\Gamma(\theta + \alpha k)}{\Gamma(\theta + n + 1)} c_{k,\alpha,\theta} (\Gamma(1 - \alpha) s_\alpha(n, k - 1) + (n - \alpha k) s_\alpha(n, k)) \\ &= \frac{\Gamma(\theta + \alpha k)}{\Gamma(\theta + n + 1)} c_{k,\alpha,\theta} s_\alpha(n + 1, k), \end{aligned}$$

which completes the induction. As a consequence, the block counting process of the two-parameter Poisson–Dirichlet coalescent has total rates

$$\begin{aligned} q_i &= \sum_{j=1}^{i-1} q_{ij} = \sum_{j=1}^{i-1} \mathbb{P}(K_i = j) = 1 - \mathbb{P}(K_i = i) \\ &= 1 - c_{i,\alpha,\theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + i)} s_\alpha(i, i) \\ &= 1 - \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + i)} \prod_{k=1}^i \frac{\Gamma(\theta + 1 + (k - 1)\alpha)}{\Gamma(\theta + k\alpha)}, \quad i \in \mathbb{N}. \end{aligned}$$

For $\alpha = 0$ the total rates reduce to $q_i = 1 - \theta^i \Gamma(\theta) / \Gamma(\theta + i)$, $i \in \mathbb{N}$, and for $\theta = 0$ we obtain $q_i = 1 - \alpha^{i-1}$, $i \in \mathbb{N}$.

Let us now turn to the fixation line. The rates γ_{ij} , $i < j$, of the fixation line are obtained similarly as the rates q_{ij} as follows. Since the measure ν is concentrated on Δ^* it follows from (9) and (10) that

$$\gamma_{ij} = \frac{j!}{i!} \sum_{\substack{j_1, \dots, j_i \in \mathbb{N} \\ j_1 + \dots + j_i = j}} \frac{I(j_1, \dots, j_i)}{j_1! \cdots j_i!},$$

where

$$I(j_1, \dots, j_i) := \int_{\Delta} \sum_{\substack{r_1, \dots, r_i \in \mathbb{N} \\ \text{all distinct}}} x_{r_1}^{j_1} \cdots x_{r_i}^{j_i} \left(1 - \sum_{k=1}^i x_{r_k} \right) \nu(dx).$$

By [7, Eq. (2.1)], $I(j_1, \dots, j_i) = \int_{\mathbb{R}^i} x_1^{j_1} \cdots x_i^{j_i} (1 - \sum_{k=1}^i x_k) \mu_i(dx_1, \dots, dx_i)$, where μ_i denotes the i th correlation measure associated with the Poisson–Dirichlet distribution. The density (correlation function) of μ_i is known explicitly (see, for example, [7, Theorem 2.1]) and we obtain $I(j_1, \dots, j_i) = c_{i,\alpha,\theta} \int_{\Delta_i} x_1^{j_1 - \alpha - 1} \cdots x_i^{j_i - \alpha - 1} (1 - \sum_{k=1}^i x_k)^{\theta + \alpha i} dx_1 \cdots dx_i$. The last integral is known (Liouville’s integration formula), and it follows that

$$I(j_1, \dots, j_i) = c_{i,\alpha,\theta} \frac{\Gamma(j_1 - \alpha) \cdots \Gamma(j_i - \alpha) \Gamma(\theta + \alpha i + 1)}{\Gamma(\theta + j + 1)},$$

$j := j_1 + \dots + j_i > i$. Plugging this expression into the above formula for γ_{ij} leads to

$$\begin{aligned} \gamma_{ij} &= c_{i,\alpha,\theta} \frac{\Gamma(\theta + \alpha i + 1)}{\Gamma(\theta + j + 1)} \frac{j!}{i!} \sum_{\substack{j_1, \dots, j_i \in \mathbb{N} \\ j_1 + \dots + j_i = j}} \frac{\Gamma(j_1 - \alpha) \cdots \Gamma(j_i - \alpha)}{j_1! \cdots j_i!} \\ &= c_{i,\alpha,\theta} \frac{\Gamma(\theta + \alpha i + 1)}{\Gamma(\theta + j + 1)} s_\alpha(j, i), \quad i < j. \end{aligned} \tag{21}$$

For $\alpha = 0$ the rate γ_{ij} reduces to

$$\gamma_{ij} = \theta^i \frac{\Gamma(\theta + 1)}{\Gamma(\theta + j + 1)} s(j, i), \quad i < j$$

whereas for $\theta = 0$ we obtain

$$\gamma_{ij} = \frac{\alpha^i}{(\Gamma(1-\alpha))^i} \frac{i!}{j!} s_\alpha(j, i) = \alpha^i \frac{i!}{j!} S(j, i; -1, -\alpha, 0), \quad i < j.$$

In particular,

$$q_{i, \leq j} = \sum_{k=1}^j q_{ik} = \frac{1}{\Gamma(\theta + i)} \sum_{k=1}^j c_{k, \alpha, \theta} \Gamma(\theta + \alpha k) s_\alpha(i, k), \quad i > j, \quad (22)$$

and

$$\gamma_{j, \geq i} = \sum_{k=i}^{\infty} \gamma_{jk} = c_{j, \alpha, \theta} \Gamma(\theta + \alpha j + 1) \sum_{k=i}^{\infty} \frac{s_\alpha(k, j)}{\Gamma(\theta + k + 1)}, \quad i > j. \quad (23)$$

The two expressions (22) and (23) are equal by duality (Theorem 2.3). The equality of (22) and (23) also follows from [20, Lemma 4.1], applied to the Markov chain K . Alternatively, one may apply Lemma 6.1 in the appendix with $a := -1$, $b := -\alpha$, $r := 0$ and $t := \theta$. Note however that formally the case $\theta = 0$ is not covered by Lemma 6.1. As a last option one may prove the equality of (22) and (23) directly (using the recursion for generalized Stirling numbers) as follows. We have

$$\begin{aligned} & q_{ki} - q_{k+1, i} \\ &= c_{i, \alpha, \theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + k)} s_\alpha(k, i) - c_{i, \alpha, \theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + k + 1)} s_\alpha(k + 1, i) \\ &= c_{i, \alpha, \theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + k)} s_\alpha(k, i) \\ &\quad - c_{i, \alpha, \theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + k + 1)} (\Gamma(1 - \alpha) s_\alpha(k, i - 1) + (k - \alpha i) s_\alpha(k, i)) \\ &= c_{i, \alpha, \theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + k + 1)} s_\alpha(k, i) ((\theta + k) - (k - \alpha i)) \\ &\quad - c_{i, \alpha, \theta} \frac{\Gamma(\theta + \alpha i)}{\Gamma(\theta + k + 1)} \Gamma(1 - \alpha) s_\alpha(k, i - 1) \\ &= c_{i, \alpha, \theta} \frac{\Gamma(\theta + 1 + \alpha i)}{\Gamma(\theta + k + 1)} s_\alpha(k, i) - c_{i-1, \alpha, \theta} \frac{\Gamma(\theta + 1 + (i-1)\alpha)}{\Gamma(\theta + k + 1)} s_\alpha(k, i - 1). \end{aligned}$$

Summation over all $i \in \{1, \dots, j\}$ yields

$$q_{k, \leq j} - q_{k+1, \leq j} = c_{j, \alpha, \theta} \frac{\Gamma(\theta + 1 + \alpha j)}{\Gamma(\theta + k + 1)} s_\alpha(k, j).$$

Another summation over all $k \geq i$ yields $q_{i, \leq j} = c_{j, \alpha, \theta} \Gamma(\theta + 1 + \alpha j) \sum_{k=i}^{\infty} s_\alpha(k, j) / \Gamma(\theta + k + 1)$, which shows that (22) and (23) coincide.

5 Proofs

Proof. (of Proposition 2.1) The formulas (4) and (6) for the rates q_{ij} and the total rates q_i of the block counting process are known from the literature [5, Eqs. (1.2) and (1.3)]. For given $x = (x_r)_{r \in \mathbb{N}} \in \Delta$ the block counting process jumps from ∞ to $j \in \mathbb{N}$ if and only if $x_1 + \dots + x_j = 1$ and $x_1, \dots, x_j > 0$, i.e. if and only if $x \in \Delta_j \setminus \Delta_{j-1}$ with the convention $\Delta_0 := \emptyset$. Integration with respect to ν yields $q_{\infty j} = \nu(\Delta_j \setminus \Delta_{j-1}) = \nu(\Delta_j) - \nu(\Delta_{j-1})$ for all $j \in \mathbb{N}$. Since the generator $Q = (q_{ij})_{i, j \in S}$ is conservative, it follows that $q_{\infty \infty} = -\sum_{j \in \mathbb{N}} q_{\infty j} = -\sum_{j \in \mathbb{N}} (\nu_j - \nu_{j-1}) = -\lim_{n \rightarrow \infty} \nu(\Delta_n) = -\nu(\Delta_f)$. \square

Proof. (of Proposition 2.2) We generalize Hénard's proof of Lemma 2.3 in [9]. Recall the pathwise definition of the fixation line based on the lookdown construction provided in the introduction. Assume first that $\Xi(\{0\}) = 0$. The fixation line jumps from $i \in \mathbb{N}$ to $j \in \mathbb{N}$ with $j > i$ if and only if there exists $k \in \{1, \dots, i\}$ and $1 \leq r_1 < \dots < r_k$ such that

- (i) exactly $i - k$ of the individuals $1, \dots, j$ belong to $J_0 := \bigcup_{r \in \mathbb{N}} J_r$,
- (ii) for every $l \in \{1, \dots, k\}$ at least one of the individuals $1, \dots, j$ belongs to J_{r_l} and
- (iii) the individual $j + 1$ does not belong to $J_{r_1} \cup \dots \cup J_{r_k}$.

For fixed $x = (x_r)_{r \in \mathbb{N}} \in \Delta$ this event has probability

$$\binom{j}{i-k} (1 - |x|)^{i-k} \sum_{\substack{i_1, \dots, i_k \in \mathbb{N} \\ i_1 + \dots + i_k = j - (i-k)}} \frac{(j - (i-k))!}{i_1! \dots i_k!} x_{r_1}^{i_1} \dots x_{r_k}^{i_k} \left(1 - \sum_{l=1}^k x_{r_l}\right).$$

Summing this probability over all $k \in \{1, \dots, i\}$ and $1 \leq r_1 < \dots < r_k$ and integrating with respect to the law ν yields $\gamma_{ij} = \int_{\Delta} \sum_{k=1}^i g_{ijk}(x) \nu(dx)$ with $g_{ijk}(x)$ defined in (10). From the definition of $Y(\cdot, x)$ in (3) it follows that $\sum_{k=1}^i g_{ijk}(x) = \mathbb{P}(Y(j, x) = i, Y(j+1, x) = i+1)$.

If $\Xi(\{0\}) > 0$ then the rate γ_{ij} increases by $\Xi(\{0\}) \binom{j}{2} \delta_{j, i+1}$, since $\binom{j}{2} \delta_{j, i+1}$ is the rate at which the fixation line of the Kingman coalescent jumps from i to j . Thus (9) is established. Similarly, given $x = (x_r)_{r \in \mathbb{N}} \in \Delta$, the fixation line jumps from $i \in \mathbb{N}$ to ∞ if and only if $x_1 + \dots + x_i = 1$, i.e. if and only if $x \in \Delta_i$. Integration with respect to ν yields $\gamma_{i\infty} = \nu(\Delta_i)$, $i \in \mathbb{N}$. Clearly, $\gamma_{\infty\infty} = 0$, since the state ∞ is absorbing.

It remains to determine the total rates γ_i , $i \in \mathbb{N}$. From the definition of $Y(\cdot, x)$ in (3) via the paintbox construction it follows that $Y(j+1, x) - Y(j, x) \in \{0, 1\}$ for all $j \in \mathbb{N}$ and $x \in \Delta$. Thus, for all $i, j \in \mathbb{N}$, $\mathbb{P}(Y(j, x) = i, Y(j+1, x) = i+1) = \mathbb{P}(Y(j, x) \leq i, Y(j+1, x) > i) = \mathbb{P}(Y(j, x) \leq i) - \mathbb{P}(Y(j+1, x) \leq i)$. Summation over all $j \in \mathbb{N}$ with $j > i$ yields

$$\begin{aligned} \sum_{\substack{j \in \mathbb{N} \\ j > i}} \mathbb{P}(Y(j, x) = i, Y(j+1, x) = i+1) &= \sum_{\substack{j \in \mathbb{N} \\ j > i}} (\mathbb{P}(Y(j, x) \leq i) - \mathbb{P}(Y(j+1, x) \leq i)) \\ &= \mathbb{P}(Y(i+1, x) \leq i) - \lim_{k \rightarrow \infty} \mathbb{P}(Y(k, x) \leq i) \\ &= \begin{cases} \mathbb{P}(Y(i+1, x) \leq i) & \text{if } x \in \Delta \setminus \Delta_i, \\ 0 & \text{if } x \in \Delta_i, \end{cases} \end{aligned}$$

since $\mathbb{P}(Y(k, x) \leq i) \rightarrow 0$ as $k \rightarrow \infty$ if $x \in \Delta \setminus \Delta_i$ and $\mathbb{P}(Y(k, x) \leq i) = 1$ for all $k \in \mathbb{N}$ if $x \in \Delta_i$. Thus, the total rates of the fixation line are

$$\begin{aligned} \gamma_i &= \gamma_{i\infty} + \sum_{\substack{j \in \mathbb{N} \\ j > i}} \gamma_{ij} \\ &= \gamma_{i\infty} + \Xi(\{0\}) \binom{i+1}{2} + \int_{\Delta \setminus \Delta_i} \mathbb{P}(Y(i+1, x) \leq i) \nu(dx) \\ &= \Xi(\{0\}) \binom{i+1}{2} + \int_{\Delta} \mathbb{P}(Y(i+1, x) \leq i) \nu(dx), \quad i \in \mathbb{N}. \end{aligned}$$

A comparison with the total rate q_i of the block counting process shows that $\gamma_i = q_{i+1}$, $i \in \mathbb{N}$. \square

Proof. (of Theorem 2.3) From $Y(k+1, x) - Y(k, x) \in \{0, 1\}$ for all $k \in \mathbb{N}$ and $x \in \Delta$ we conclude that

$$\begin{aligned} \mathbb{P}(Y(k, x) = j, Y(k+1, x) = j+1) &= \mathbb{P}(Y(k, x) \leq j, Y(k+1, x) > j) \\ &= \mathbb{P}(Y(k, x) \leq j) - \mathbb{P}(Y(k+1, x) \leq j) \end{aligned}$$

for all $j, k \in \mathbb{N}$ and $x \in \Delta$. Integration with respect to ν and taking the formula (9) for the rates of the fixation line into account, it follows for all $j, k \in \mathbb{N}$ with $j < k$ that

$$\gamma_{jk} = \Xi(\{0\}) \binom{k}{2} \delta_{k, j+1} + \int_{\Delta} \mathbb{P}(Y(k, x) = j, Y(k+1, x) = j+1) \nu(dx)$$

$$\begin{aligned}
&= \Xi(\{0\}) \binom{k}{2} \delta_{j,k-1} + \int_{\Delta} (\mathbb{P}(Y(k, x) \leq j) - \mathbb{P}(Y(k+1, x) \leq j)) \nu(dx) \\
&= \sum_{l=1}^j \left(\Xi(\{0\}) \binom{k}{2} \delta_{l,k-1} + \int_{\Delta} \mathbb{P}(Y(k, x) = l) \nu(dx) \right. \\
&\quad \left. - \Xi(\{0\}) \binom{k+1}{2} \delta_{lk} - \int_{\Delta} \mathbb{P}(Y(k+1, x) = l) \nu(dx) \right) \\
&= \sum_{l=1}^j (q_{kl} - q_{k+1,l}) = q_{k,\leq j} - q_{k+1,\leq j}, \quad j, k \in \mathbb{N}, j < k,
\end{aligned}$$

where the second last equality holds by (4). Let $i, j \in \mathbb{N}$ with $i > j$. Summing over all $k \in \mathbb{N}$ with $k \geq i$ yields

$$\sum_{\substack{k \in \mathbb{N} \\ k \geq i}} \gamma_{jk} = \sum_{\substack{k \in \mathbb{N} \\ k \geq i}} (q_{k,\leq j} - q_{k+1,\leq j}) = q_{i,\leq j} - \lim_{k \rightarrow \infty} q_{k,\leq j} = q_{i,\leq j} - \nu(\Delta_j).$$

The last equality holds since, by (4),

$$\begin{aligned}
q_{k,\leq j} &= \sum_{l=1}^j q_{kl} = \Xi(\{0\}) \binom{k}{2} \delta_{j,k-1} + \int_{\Delta} \mathbb{P}(Y(k, x) \leq j) \nu(dx) \\
&\rightarrow \int_{\Delta} 1_{\Delta_j}(x) \nu(dx) = \nu(\Delta_j)
\end{aligned}$$

as $k \rightarrow \infty$ by dominated convergence. Note that $\mathbb{P}(Y(k, x) \leq j) \leq \mathbb{P}(Y(j+1, x) \leq j)$ for all $k > j$ and that the dominating map $x \mapsto \mathbb{P}(Y(j+1, x) \leq j)$ is ν -integrable.

Since $\gamma_{j\infty} = \nu(\Delta_j)$ it follows that

$$q_{i,\leq j} = \sum_{\substack{k \in S \\ k \geq i}} \gamma_{jk} = \gamma_{j,\geq i} \tag{24}$$

for all $i, j \in \mathbb{N}$ with $i > j$. Eq. (24) holds as well for $i, j \in \mathbb{N}$ with $i \leq j$ since in this case both sides in (24) are equal to 0. Moreover, $q_{i,\leq \infty} = 0 = \gamma_{\infty,\geq i}$ for all $i \in S$ and $q_{\infty,\leq j} = \nu(\Delta_j) = \gamma_{j\infty} = \gamma_{j,\geq \infty}$ for all $j \in \mathbb{N}$. Thus, (24) holds for all $i, j \in S$.

Let $Q = (q_{ij})_{i,j \in S}$ and $\Gamma = (\gamma_{ij})_{i,j \in S}$ denote the generator matrices of N and L respectively and let $H = (h_{ij})_{i,j \in S}$ denote the matrix with entries $h_{ij} := 1$ for $i \leq j$ and $h_{ij} := 0$ for $i > j$. Since $(QH)_{ij} = \sum_{k \in S, k \leq j} q_{ik} h_{kj} = \sum_{k \in S, k \leq j} q_{ik} = q_{i,\leq j}$ and $(H\Gamma^\top)_{ij} = \sum_{k \in S, k \geq i} h_{ik} \gamma_{jk} = \sum_{k \in S, k \geq i} \gamma_{jk} = \gamma_{j,\geq i}$ it follows that $QH = H\Gamma^\top$. It follows that $Q^k H = H(\Gamma^\top)^k$ for all $k \in \mathbb{N}$ and, hence, $e^{tQ} H = H(e^{t\Gamma})^\top$ for all $t \geq 0$. Since e^{tQ} and $e^{t\Gamma}$ are the transition matrices of the block counting process $N = (N_t)_{t \geq 0}$ and the fixation line $L = (L_t)_{t \geq 0}$ respectively, this shows that N is Siegmund dual to L with respect to the kernel H . \square

Remark. For Λ -coalescents Lemma 2.1 of Hénard [9] essentially states the Siegmund duality of N and L and Lemma 2.4 of [9] is a reformulation of this duality in terms of the generators of N and L .

Proof. (of Theorem 2.4) For $n \in \mathbb{N}$ and $i \in \{1, \dots, n\}$ let $\tau_{n,i} := \inf\{t > 0 : i \text{ is not a singleton of } \Pi_t^{(n)}\}$ denote the length of the i th external branch of $\Pi^{(n)}$. For every $i \in \mathbb{N}$ the sequence $(\tau_{n,i})_{n \geq i}$ is non-increasing in n with $\tau_{n,i} \searrow \tau_i$ almost surely as $n \rightarrow \infty$, where $\tau_i := \inf\{t > 0 : \{i\} \text{ is not a singleton of } \Pi_t\}$ denotes the length of the i th external branch of Π . Let $t_1, \dots, t_k \geq 0$. Conditional on S_{t_1}, \dots, S_{t_k} , the probability that i is still a singleton at time t_i for all $i \in \{1, \dots, k\}$, is $S_{t_1} \cdots S_{t_k}$. Thus, $\mathbb{P}(\tau_1 > t_1, \dots, \tau_k > t_k) = \mathbb{E}(S_{t_1} \cdots S_{t_k})$. In particular, $\mathbb{P}(\tau_1 > t, \dots, \tau_k > t) = \mathbb{E}(S_t^k)$.

Proof of part a). For $n \in \mathbb{N}$ and $t \geq 0$ decompose $N_t^{(n)} = E_t^{(n)} + I_t^{(n)}$, where $E_t^{(n)} := \sum_{i=1}^n 1_{\{\tau_{n,i} > t\}}$ and $I_t^{(n)} := N_t^{(n)} - E_t^{(n)}$ denotes the number of singleton and non-singleton blocks of $\Pi_t^{(n)}$ respectively. We think of $E_t^{(n)}$ and $I_t^{(n)}$ as the number of ‘external’ and ‘internal’ blocks of $\Pi_t^{(n)}$ and proceed similar as in the proof of Theorem 3 of [18]. For $t \geq 0$ and $n, k \in \mathbb{N}$,

$$\begin{aligned} \mathbb{E}((E_t^{(n)})^k) &= \mathbb{E}((1_{\{\tau_{n,1} > t\}} + \cdots + 1_{\{\tau_{n,n} > t\}})^k) \\ &= \sum_{\substack{k_1, \dots, k_n \in \mathbb{N}_0 \\ k_1 + \dots + k_n = k}} \frac{k!}{k_1! \cdots k_n!} \mathbb{E}(1_{\{\tau_{n,1} > t\}}^{k_1} \cdots 1_{\{\tau_{n,n} > t\}}^{k_n}) \\ &= \sum_{j=1}^k \binom{n}{j} \sum_{\substack{k_1, \dots, k_j \in \mathbb{N} \\ k_1 + \dots + k_j = k}} \mathbb{E}(1_{\{\tau_{n,1} > t\}}^{k_1} \cdots 1_{\{\tau_{n,j} > t\}}^{k_j}), \end{aligned}$$

where the last equality holds since the random variables $\tau_{n,i}$, $i \in \{1, \dots, n\}$, are exchangeable. Thus,

$$\mathbb{E}((E_t^{(n)})^k) = \sum_{j=1}^k \binom{n}{j} S(k, j) \mathbb{P}(\tau_{n,1} > t, \dots, \tau_{n,j} > t), \quad t \geq 0, n, k \in \mathbb{N}, \quad (25)$$

where $\binom{n}{j} := n(n-1) \cdots (n-j+1)$ and $S(\cdot, \cdot)$ denote the Stirling numbers of the second kind. Dividing by n^k , letting $n \rightarrow \infty$ and noting that $\binom{n}{j}/n^k \rightarrow \delta_{jk}$ it follows that

$$\lim_{n \rightarrow \infty} \mathbb{E}((E_t^{(n)}/n)^k) = \mathbb{P}(\tau_1 > t, \dots, \tau_k > t) = \mathbb{E}(S_t^k), \quad k \in \mathbb{N}. \quad (26)$$

Since $0 \leq E_t^{(n)}/n \leq 1$ and $0 \leq S_t \leq 1$ the convergence (26) of moments implies the convergence $E_t^{(n)}/n \rightarrow S_t$ in distribution as $n \rightarrow \infty$. In order to show that $N_t^{(n)}/n \rightarrow S_t$ in distribution as $n \rightarrow \infty$ it remains to verify that $I_t^{(n)}/n \rightarrow 0$ in distribution as $n \rightarrow \infty$. In the following it is verified that the latter convergence even holds in L^1 . Each internal branch is generated by a collision. Thus, if C_n denotes the total number of collisions, the inequality $\mathbb{E}(I_t^{(n)}) \leq \mathbb{E}(C_n)$ holds. The assumption that the coalescent has dust ensures that $C_n/n \rightarrow 0$ in L^1 by Lemma 4.1 of [5]. Thus, $I_t^{(n)}/n \rightarrow 0$ in L^1 as $n \rightarrow \infty$, which yields the desired convergence $N_t^{(n)}/n \rightarrow S_t$ in distribution as $n \rightarrow \infty$. Thus, the convergence of the one-dimensional distributions is established.

Let us now turn to the proof of the convergence in $D_{[0,1]}[0, \infty)$. Let $(T_t^{(n)})_{t \geq 0}$ and $(T_t)_{t \geq 0}$ denote the semigroups of $(N_t^{(n)}/n)_{t \geq 0}$ and $(S_t)_{t \geq 0}$ respectively. By Ethier and Kurtz [4, p. 172, Theorem 2.11], applied with state spaces $E := [0, 1]$ and $E_n := \{j/n : j \in \{1, \dots, n\}\}$, $n \in \mathbb{N}$, and with the maps $\eta_n : E_n \rightarrow E$ and $\pi_n : B(E) \rightarrow B(E_n)$ defined via $\eta_n(x) := x$ for all $x \in E_n$ and $\pi_n f(x) := f(x)$ for all $f \in B(E)$ and all $x \in E_n$, it suffices to verify that for every $t \geq 0$ and $f \in C(E)$,

$$\lim_{n \rightarrow \infty} \sup_{x \in E_n} |T_t^{(n)} \pi_n f(x) - \pi_n T_t f(x)| = 0.$$

For $f \in C(E)$ and $x \in E_n$ we have $T_t^{(n)} \pi_n f(x) = \mathbb{E}(\pi_n f(N_{s+t}^{(n)}/n) | N_s^{(n)}/n = x) = \mathbb{E}(f(N_t^{(nx)}/n))$ and $\pi_n T_t f(x) = T_t f(x) = \mathbb{E}(f(xS_t))$. Thus, we have to verify that $\lim_{n \rightarrow \infty} \sup_{x \in E_n} |\mathbb{E}(f(N_t^{(nx)}/n)) - \mathbb{E}(f(xS_t))| = 0$. Since the polynomials are dense in $C(E)$ it suffices to verify the latter equation for monomials $f(x) = x^k$, so we have to prove that

$$\lim_{n \rightarrow \infty} \sup_{x \in E_n} |\mathbb{E}((N_t^{(nx)})^k)/n^k - x^k \mathbb{E}(S_t^k)| = 0, \quad k \in \mathbb{N}, t \geq 0.$$

Using the decomposition $N_t^{(nx)} = E_t^{(nx)} + I_t^{(nx)}$ and the facts that $I_t^{(nx)} \leq C_{nx} \leq C_n$ and that $C_n/n \rightarrow 0$ in L^1 (see Lemma 4.1 of [5]), it suffices to show that

$$\lim_{n \rightarrow \infty} \sup_{x \in E_n} |\mathbb{E}((E_t^{(nx)})^k)/n^k - x^k \mathbb{E}(S_t^k)| = 0.$$

By (25), $\mathbb{E}((E_t^{(nx)})^k) = \sum_{j=1}^k (nx)_j S(k, j) \mathbb{P}(\tau_{nx,1} > t, \dots, \tau_{nx,j} > t)$. Thus, it suffices to verify that

$$\lim_{n \rightarrow \infty} \sup_{x \in E_n} \left| \frac{(nx)_k}{n^k} \mathbb{P}(\tau_{nx,1} > t, \dots, \tau_{nx,k} > t) - x^k \mathbb{E}(S_t^k) \right| = 0.$$

Since $(nx)_k/n^k \rightarrow x^k$ as $n \rightarrow \infty$ uniformly on $[0, 1]$ it remains to prove that

$$\lim_{n \rightarrow \infty} \sup_{x \in E_n} x^k |\mathbb{P}(\tau_{nx,1} > t, \dots, \tau_{nx,k} > t) - \mathbb{E}(S_t^k)| = 0.$$

This is seen as follows. Choose a sequence $(\varepsilon_n)_{n \in \mathbb{N}}$ satisfying $\varepsilon_n \rightarrow 0$ and $n\varepsilon_n \rightarrow \infty$ (for example $\varepsilon_n := n^{-1/2}$) and distinguish the two cases $x \in E_n \cap [0, \varepsilon_n]$ and $x \in E_n \cap (\varepsilon_n, 1]$. Clearly,

$$\sup_{x \in E_n \cap [0, \varepsilon_n]} x^k |\mathbb{P}(\tau_{nx,1} > t, \dots, \tau_{nx,k} > t) - \mathbb{E}(S_t^k)| \leq 2\varepsilon_n^k \rightarrow 0, \quad n \rightarrow \infty.$$

Moreover, since $p_{t,k}(m) := \mathbb{P}(\tau_{m,1} > t, \dots, \tau_{m,k} > t)$ is non-increasing in m ($\geq k$), it follows for all $n \in \mathbb{N}$ with $n\varepsilon_n \geq k$ that

$$\begin{aligned} \sup_{x \in E_n \cap (\varepsilon_n, 1]} x^k |\mathbb{P}(\tau_{nx,1} > t, \dots, \tau_{nx,k} > t) - \mathbb{E}(S_t^k)| &\leq \sup_{x \in E_n \cap (\varepsilon_n, 1]} |p_{t,k}(nx) - \mathbb{E}(S_t^k)| \\ &\leq p_{t,k}(\lfloor n\varepsilon_n \rfloor) - \mathbb{E}(S_t^k) \rightarrow 0 \end{aligned}$$

as $n \rightarrow \infty$. The proof of part a) is complete.

Proof of part b). We have to verify that $(L_t^{(n)}/n)_{t \geq 0}$ converges in $D_{[1, \infty]}[0, \infty)$ to $(1/S_t)_{t \geq 0}$ as $n \rightarrow \infty$. Define $\varphi : D_{[0, 1]}[0, \infty) \rightarrow D_{[1, \infty]}[0, \infty)$ via $\varphi(x) := (1/x_t)_{t \geq 0}$ for all $x = (x_t)_{t \geq 0} \in D_{[0, 1]}[0, \infty)$ with the convention $1/0 := \infty$. Since the transformation φ is continuous we will (equivalently) verify that $(n/L_t^{(n)})_{t \geq 0}$ converges in $D_{[0, 1]}[0, \infty)$ to $(S_t)_{t \geq 0}$ as $n \rightarrow \infty$.

Let $F_n := \{n/j : j \in \{n, n+1, \dots\}\} \cup \{0\}$ and $F := [0, 1]$ denote the state spaces and $(U_t^{(n)})_{t \geq 0}$ and $(U_t)_{t \geq 0}$ the semigroups of $(n/L_t^{(n)})_{t \geq 0}$ and $(S_t)_{t \geq 0}$ respectively. Define $\pi_n : B(F) \rightarrow B(F_n)$ via $\pi_n f(x) := f(x)$, $f \in B(F)$, $x \in F_n$. By Ethier and Kurtz [4, p. 172, Theorem 2.11] it suffices to verify that for all $t \geq 0$ and all $f \in C(F)$,

$$\lim_{n \rightarrow \infty} \sup_{x \in F_n} |U_t^{(n)} \pi_n f(x) - \pi_n U_t f(x)| = 0.$$

For $f \in C(F)$ and $x \in F_n$ we have $U_t^{(n)} \pi_n f(x) = \mathbb{E}(\pi_n f(n/L_{s+t}^{(n)}) | n/L_s^{(n)} = x) = \mathbb{E}(f(n/L_t^{(n/x)}))$ and $\pi_n U_t f(x) = U_t f(x) = \mathbb{E}(f(xS_t))$. Thus, we have to verify that

$$\lim_{n \rightarrow \infty} \sup_{x \in F_n} |\mathbb{E}(f(n/L_t^{(n/x)})) - \mathbb{E}(f(xS_t))| = 0.$$

Since the polynomials are dense in $C(F)$ it suffices to verify the latter equation for monomials $f(x) = x^k$, so we have to prove that $\lim_{n \rightarrow \infty} \sup_{x \in F_n} |\mathbb{E}((n/L_t^{(n/x)})^k) - x^k \mathbb{E}(S_t^k)| = 0$ for all $t \geq 0$ and $k \in \mathbb{N}$. In the following it is even shown that

$$\lim_{n \rightarrow \infty} \sup_{x \in [0, 1]} |\mathbb{E}((n/L_t^{(\lfloor n/x \rfloor)})^k) - x^k \mathbb{E}(S_t^k)| = 0, \quad t \geq 0, k \in \mathbb{N}, \quad (27)$$

where $\lfloor n/x \rfloor := \max\{z \in \mathbb{Z} : z \leq n/x\}$.

For $m \in \mathbb{N}$, $t \geq 0$ and $y \in (0, 1]$, it follows by duality (Theorem 2.3 applied with $i := \lfloor m/y \rfloor := \min\{z \in \mathbb{Z} : z \geq m/y\}$ and $j := m$)

$$\begin{aligned} \mathbb{P}(m/L_t^{(m)} \leq y) &= \mathbb{P}(L_t^{(m)} \geq m/y) = \mathbb{P}(L_t^{(m)} \geq \lfloor m/y \rfloor) \\ &= \mathbb{P}(N_t^{(\lfloor m/y \rfloor)} \leq m) = \mathbb{P}\left(\frac{N_t^{(\lfloor m/y \rfloor)}}{\lfloor m/y \rfloor} \leq \frac{m}{\lfloor m/y \rfloor}\right). \end{aligned}$$

Since $N_t^{(m)}/m \rightarrow S_t$ in distribution as $m \rightarrow \infty$ by part a) of Theorem 2.4, which is already proven, and since $\lim_{m \rightarrow \infty} m/\lceil m/y \rceil = y$, we conclude that $\lim_{m \rightarrow \infty} \mathbb{P}(m/L_t^{(m)} \leq y) = \mathbb{P}(S_t \leq y)$, if $y \in (0, 1]$ is a continuity point of the distribution function of S_t . The point $y = 0$ has to be treated separately. For all $m \in \mathbb{N}$ we have $\mathbb{P}(m/L_t^{(m)} \leq 0) = \mathbb{P}(L_t^{(m)} = \infty) = \lim_{n \rightarrow \infty} \mathbb{P}(L_t^{(m)} \geq n) = \lim_{n \rightarrow \infty} \mathbb{P}(N_t^{(n)} \leq m) = \lim_{n \rightarrow \infty} \mathbb{P}(N_t^{(n)}/n \leq m/n) = \mathbb{P}(S_t \leq 0)$, if $y = 0$ is a continuity point of the distribution function of S_t . The pointwise convergence of the distribution functions implies the convergence $m/L_t^{(m)} \rightarrow S_t$ in distribution as $m \rightarrow \infty$.

Fix $x \in (0, 1]$. Replacing m by $\lfloor n/x \rfloor$ it follows by an application of Slutsky's theorem that $n/L_t^{(\lfloor n/x \rfloor)} \rightarrow xS_t$ in distribution as $n \rightarrow \infty$. This convergence obviously holds as well for $x = 0$ with the convention $n/0 := \infty$. Noting that the map $y \mapsto y^k$ is bounded and continuous on $[0, 1]$ we conclude that

$$\lim_{n \rightarrow \infty} \mathbb{E}((n/L_t^{(\lfloor n/x \rfloor)})^k) = x^k \mathbb{E}(S_t^k), \quad t \geq 0, k \in \mathbb{N}, x \in [0, 1].$$

In order to see that this pointwise convergence holds even uniformly for all $x \in [0, 1]$ we proceed as follows. Fix $t \geq 0$, $k \in \mathbb{N}$ and $n \in \mathbb{N}$. By the pathwise construction of the fixation line, we have $L_t^{(1)} \leq L_t^{(2)} \leq \dots$. It follows that the map $x \mapsto \mathbb{E}((n/L_t^{(\lfloor n/x \rfloor)})^k)$ is non-decreasing on $[0, 1]$. Clearly, the limiting map $x \mapsto x^k \mathbb{E}(S_t^k)$ is non-decreasing, bounded and continuous on $[0, 1]$. Thus, the pointwise convergence holds even uniformly for all $x \in [0, 1]$. Note that the proof that this pointwise convergence holds even uniformly works the same as the proof that pointwise convergence of distribution functions is uniform if the limiting distribution function is continuous (Pólya [25, Satz I]). Therefore, (27) is established. The proof is complete. \square

6 Appendix

We establish a sort of duality relation for generalized Stirling numbers. Let $a, b, r \in \mathbb{R}$ and suppose that $t \notin \{0, a, 2a, 3a, \dots\}$ such that we can define

$$q_{ij} := \frac{(t-r|b)_j}{(t|a)_i} S(i, j), \quad i, j \in \mathbb{N}_0,$$

where $(t|a)_i := \prod_{k=0}^{i-1} (t-ak)$ and the coefficients $S(i, j) := S(i, j; a, b, r)$ are the generalized Stirling numbers as defined in [11]. The recursion $S(i+1, j) = S(i, j-1) + (jb-ia+r)S(i, j)$ for the generalized Stirling numbers (see [11, Theorem 1]) obviously transforms into the recursion

$$q_{i+1, j} = \frac{t-r-(j-1)b}{t-ia} q_{i, j-1} + \frac{jb-ia+r}{t-ia} q_{ij} \quad (28)$$

for the quantities q_{ij} ($q_{i, -1} := 0$). Note that $\sum_{j=0}^{\infty} q_{ij} = 1$ for all $i \in \mathbb{N}_0$. For $i, j \in \mathbb{N}_0$ we define $q_{i, \leq j} := \sum_{k=0}^j q_{ik}$.

Lemma 6.1 *Fix $j \in \mathbb{N}_0$ and suppose that the limit $\lim_{k \rightarrow \infty} q_{k, \leq j}$ exists. Then, for all $i \in \mathbb{N}_0$,*

$$q_{i, \leq j} - \lim_{k \rightarrow \infty} q_{k, \leq j} = \sum_{k=i}^{\infty} \frac{t-r-jb}{t-ka} q_{kj}. \quad (29)$$

Remark. At a first glance Lemma 6.1 looks somewhat technical and does not seem to have many applications. Indeed, in general it seems to be not straightforward to verify the existence of the limit $\lim_{k \rightarrow \infty} q_{k, \leq j}$ and to determine this limit (if it exists). However, for particular parameter choices (for instance for $a \leq 0$, $b > 0$, $r = 0$ and $t > 0$ an integer multiple of b), the q_{ij} turn out to be non-negative. In this case there exists a random variable K_i with distribution $\mathbb{P}(K_i = j) = q_{ij}$, $j \in \mathbb{N}_0$. Based on the recursion (28) the sequence $K := (K_i)_{i \in \mathbb{N}_0}$ can be even constructed such that K is a Markov chain with

initial state $K_0 = 0$ satisfying $K_{i+1} - K_i \in \{0, 1\}$ for all $i \in \mathbb{N}_0$. Hence, $q_{i,\leq j} = \mathbb{P}(K_i \leq j)$ is non-increasing in i , which ensures the existence of the limit $\lim_{i \rightarrow \infty} q_{i,\leq j}$. If all states $0, 1, \dots, j$ of the chain K are transient, then $\lim_{i \rightarrow \infty} q_{i,\leq j} = 0$ and (29) reduces to

$$\sum_{k=0}^j q_{ik} = \sum_{k=i}^{\infty} \frac{t-r-jb}{t-ka} q_{kj}. \quad (30)$$

Roughly speaking, (30) is a sort of analytic reformulation of a particular Siegmund duality. For typical examples we refer the reader to the equality of (17) and (18) for the Dirichlet coalescent and to the equality of (22) and (23) for the Poisson–Dirichlet coalescent.

Proof. (of Lemma 6.1) The proof of Lemma 6.1 is purely analytic and straightforward. For all $k, i \in \mathbb{N}_0$ we have

$$\begin{aligned} q_{ki} - q_{k+1,i} &= q_{ki} - \frac{t-r-(i-1)b}{t-ka} q_{k,i-1} - \frac{ib-ka+r}{t-ka} q_{ki} \\ &= \frac{t-r-ib}{t-ka} q_{ki} - \frac{t-r-(i-1)b}{t-ka} q_{k,i-1}. \end{aligned}$$

Summation over all $i \in \{0, \dots, j\}$ yields

$$q_{k,\leq j} - q_{k+1,\leq j} = \frac{t-r-jb}{t-ka} q_{kj}.$$

Another summation over all $k \geq i$ yields the result. \square

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