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The Law of the Hitting Times to Points by a Stable Lévy Process with No Negative Jumps

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Let $X = (X_t)_{t \ge 0}$ be a stable Lévy process of index $\alpha \in (1,2)$ with the Lévy measure $\nu(dx) = (c/x^{1+\alpha})\, I_{(0,\infty)}(x)\, dx$ for $c > 0$, let $x > 0$ be given and fixed, and let $\tau_x = \inf\{\, t > 0 : X_t = x \,\}$ denote the first hitting time of X to x . Then the density function f_{τ_x} of τ_x admits the following series representation:

$$f_{\tau_x}(t) = \frac{x^{\alpha-1}}{\pi (c\Gamma(-\alpha)\, t)^{2-1/\alpha}} \sum_{n=1}^{\infty} \Bigg[(-1)^{n-1} \sin(\pi/\alpha) \frac{\Gamma(n-1/\alpha)}{\Gamma(\alpha n - 1)} \Big(\frac{x^\alpha}{c\Gamma(-\alpha)\, t} \Big)^{n-1} - \sin\Big(\frac{n\pi}{\alpha} \Big) \frac{\Gamma(1+n/\alpha)}{n!} \Big(\frac{x^\alpha}{c\Gamma(-\alpha)\, t} \Big)^{(n+1)/\alpha - 1} \Bigg]$$

for $t > 0$. In particular, this yields $f_{\tau_x}(0+) = 0$ and

$$f_{\tau_x}(t) \sim \frac{x^{\alpha-1}}{\Gamma(\alpha-1)\, \Gamma(1/\alpha)} \, (c\Gamma(-\alpha)\, t)^{-2+1/\alpha}$$

as $t \to \infty$. The method of proof exploits a simple identity linking the law of τ_x to the laws of X_t and $\sup_{0 \le s \le t} X_s$ that makes a Laplace inversion amenable. A simpler series representation for f_{τ_x} is also known to be valid when $x < 0$.

1. Introduction

If a Lévy process $X = (X_t)_{t \ge 0}$ jumps upwards, then it is much harder to derive a closed form expression for the distribution function of its first passage time $\tau_{(x,\infty)}$ over a strictly positive level x , and in the existing literature such expressions seem to be available only when X has no positive jumps (unless the Lévy measure is discrete). A notable exception to this rule is the recent paper [1] where an explicit series representation for the density function of $\tau_{(x,\infty)}$ was derived when X is a stable Lévy process of index $\alpha \in (1,2)$ having the Lévy measure given by $\nu(dx) = (c/x^{1+\alpha})\, I_{(0,\infty)}(x)\, dx$ with $c > 0$ given and fixed. This was done by performing a time-space inversion of the Wiener-Hopf factor corresponding to the Laplace transform of $(t,y) \mapsto \mathsf{P}(S_t > y)$ where $S_t = \sup_{0 \le s \le t} X_s$ for $t > 0$ and $y > 0$.

Motivated by this development our purpose in this note is to search for a similar series representation associated with the first hitting time τ_x of X to a strictly positive level x

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itself. Clearly, since X jumps upwards and creeps downwards, τ_x will happen strictly after $\tau_{(x,\infty)}$, and since X reaches x by creeping through it independently from the past prior to $\tau_{(x,\infty)}$, one can exploit known expressions for the latter portion of the process and derive the Laplace transform for $(t,y) \mapsto \mathsf{P}(\tau_y > t)$. This was done in [6, Theorem 1] and is valid for any Lévy process with no negative jumps (excluding subordinators). A direct Laplace inversion of the resulting expression appears to be difficult, however, and we show that a simple (Chapman-Kolmogorov type) identity which links the law of τ_x to the laws of X_t and S_t proves helpful in this context (due largely to the scaling property of X). It enables us to connect the old result of [13] with the recent result of [1] through an additive factorisation of the Laplace transform of $(t,y) \mapsto \mathsf{P}(\tau_y > t)$. This makes the Laplace inversion possible term by term and yields an explicit series representation for the density function of τ_x.

2. Result and proof

1. Let $X = (X_t)_{t \ge 0}$ be a stable Lévy process of index $\alpha \in (1,2)$ whose characteristic function is given by

$$\mathsf{E} e^{i\lambda X_t} = \exp\left(t \int_0^\infty (e^{i\lambda x} - 1 - i\lambda x) \, \frac{dx}{\Gamma(-\alpha)\, x^{1+\alpha}} \right) = e^{t(-i\lambda)^\alpha} \tag{2.1}$$

for $\lambda \in I\!R$ and $t \ge 0$. It follows that the Laplace transform of X is given by

$$\mathsf{E} e^{-\lambda X_t} = e^{t\lambda^\alpha} \tag{2.2}$$

for $\lambda \ge 0$ and $t \ge 0$ (the left-hand side being $+\infty$ for $\lambda < 0$). From (2.2) we see that the Laplace exponent of X equals $\psi(\lambda) = \lambda^\alpha$ for $\lambda \ge 0$ and $\varphi(p) := \psi^{-1}(p) = p^{1/\alpha}$ for $p \ge 0$.

2. The following properties of X are readily deduced from (2.1) and (2.2) using standard means (see e.g. [2] and [9]): the law of $(X_{ct})_{t \ge 0}$ is the same as the law of $(c^{1/\alpha} X_t)_{t \ge 0}$ for each $c > 0$ given and fixed (scaling property); X is a martingale with $\mathsf{E} X_t = 0$ for all $t \ge 0$; X jumps upwards (only) and creeps downwards (in the sense that $\mathsf{P}(X_{\tau_{(-\infty,x)}} = x) = 1$ for $x < 0$ where $\tau_{(-\infty,x)} = \inf\{\, t > 0 : X_t < x \,\}$ is the first passage time of X over x); X has sample paths of unbounded variation; X oscillates from $-\infty$ to $+\infty$ (in the sense that $\liminf_{t \to \infty} X_t = -\infty$ and $\limsup_{t \to \infty} X_t = +\infty$ both a.s.); the starting point 0 of X is regular (for both $(-\infty,0)$ and $(0,+\infty)$). Note that the constant $c = 1/\Gamma(-\alpha)$ in the Lévy measure $\nu(dx) = (c/x^{1+\alpha})\, dx$ of X is chosen/fixed for convenience so that X converges in law to $\sqrt{2}\, B$ as $\alpha \uparrow 2$ where B is a standard Brownian motion, and all the facts throughout can be extended to a general constant $c > 0$ using the scaling property of X.

3. Letting f_{X_1} denote the density function of X_1, the following series representation is known to be valid (see e.g. (14.30) in [14, p. 88]):

$$f_{X_1}(x) = \sum_{n=1}^\infty \frac{\sin(n\pi/\alpha)}{\pi} \, \frac{\Gamma(1+n/\alpha)}{n!} \, x^{n-1} \tag{2.3}$$

for $x \in I\!R$. Setting $S_1 = \sup_{0 \le t \le 1} X_t$ and letting f_{S_1} denote the density function of S_1, the following series representation was recently derived in [1, Theorem 1]:

$$f_{S_1}(x) = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\sin(\pi/\alpha)}{\pi} \frac{\Gamma(n-1/\alpha)}{\Gamma(\alpha n-1)}\, x^{\alpha n-2} \tag{2.4}$$

for $x > 0$. Clearly, the series representations (2.3) and (2.4) extend to $t \neq 1$ by the scaling property of X since $X_t =^{\text{law}} t^{1/\alpha} X_1$ and $S_t := \sup_{0 \le s \le t} X_s =^{\text{law}} t^{1/\alpha} S_1$ for $t > 0$.

4. Consider the first hitting time of X to x given by

$$\tau_x = \inf\{\, t > 0 : X_t = x \,\} \tag{2.5}$$

for $x > 0$. Then it is known (see (2.16) in [6]) that the time-space Laplace transform equals

$$\int_0^\infty e^{-\lambda x}\, \mathsf{E}(e^{-p\tau_x})\, dx = \frac{1}{\lambda-\varphi(p)} + \frac{1}{\varphi'(p)\,(p-\psi(\lambda))} = \frac{1}{\lambda - p^{1/\alpha}} + \frac{\alpha}{p^{-1+1/\alpha}(p-\lambda^\alpha)} \tag{2.6}$$

for $\lambda > 0$ and $p > 0$. Note that this can be rewritten as follows:

$$\int_0^\infty e^{-pt} dt \int_0^\infty e^{-\lambda x}\, \mathsf{P}(\tau_x > t)\, dx = \frac{1}{\lambda p} + \frac{1}{p(p^{1/\alpha}-\lambda)} - \frac{\alpha}{p^{1/\alpha}(p-\lambda^\alpha)} \tag{2.7}$$

for $\lambda > 0$ and $p > 0$.

Let $I\!\!L_p^{-1}$ denote the inverse Laplace transform with respect to p. Using that $1/(p(p^{1/\alpha} - \lambda)) = \sum_{n=1}^\infty \lambda^{n-1}/p^{1+n/\alpha}$ and $I\!\!L_p^{-1}[1/p^a] = t^{a-1}/\Gamma(a)$ for $a > 0$, it is easily verified that

$$I\!\!L_p^{-1}\Big[\frac{1}{p(p^{1/\alpha}-\lambda)}\Big](t) = \frac{1}{\lambda}\Big[E_{1/\alpha}(\lambda t^{1/\alpha}) - 1\Big] \tag{2.8}$$

for $t > 0$ where $E_a(x) = \sum_{n=0}^\infty x^n/\Gamma(an{+}1)$ denotes the Mittag-Leffler function. On the other hand, by (3) in [8, p. 238] we find

$$I\!\!L_p^{-1}\Big[\frac{1}{p^{1/\alpha}(p-\lambda^\alpha)}\Big](t) = \frac{1}{\Gamma(1/\alpha)} \frac{e^{\lambda^\alpha t}}{\lambda}\, \gamma(1/\alpha, \lambda^\alpha t) \tag{2.9}$$

for $t > 0$ where $\gamma(a, x) = \int_0^x y^{a-1} e^{-y}\, dy$ denotes the incomplete gamma function. Combining (2.7) with (2.8) and (2.9) we get

$$\begin{aligned} \int_0^\infty e^{-\lambda x}\, \mathsf{P}(\tau_x > t)\, dx &= \frac{1}{\lambda} E_{1/\alpha}(\lambda t^{1/\alpha}) - \frac{\alpha}{\Gamma(1/\alpha)} \frac{e^{\lambda^\alpha t}}{\lambda}\, \gamma(1/\alpha, \lambda^\alpha t) \\ &= \frac{\alpha}{\lambda}\Big[\frac{\alpha}{\Gamma(1/\alpha)}\, e^{\lambda^\alpha t} \int_{\lambda t^{1/\alpha}}^\infty e^{-z^\alpha} dz - e^{\lambda^\alpha t} + \frac{1}{\alpha} E_{1/\alpha}(\lambda t^{1/\alpha})\Big] \end{aligned} \tag{2.10}$$

for $\lambda > 0$ and $t > 0$.

The first and the third term on the right-hand side of (2.10) may now be recognised as the Laplace transforms of particular functions considered in [1] and [13] respectively (recall also (2.2) above). The proof of the following theorem provides a simple probabilistic argument (of Chapman-Kolmogorov type) for this additive factorisation (see Remark 1 below).

Theorem 1. *Let* $X = (X_t)_{t \ge 0}$ *be a stable Lévy process of index* $\alpha \in (1,2)$ *with the Lévy measure* $\nu(dx) = (c/x^{1+\alpha})\, I_{(0,\infty)}(x)\, dx$ *for* $c > 0$, *let* $x > 0$ *be given and fixed, and let* τ_x *denote the first hitting time of* X *to* x . *Then the density function* f_{τ_x} *of* τ_x *admits the following series representation:*

$$f_{\tau_x}(t) = \frac{x^{\alpha-1}}{\pi(c\Gamma(-\alpha)\,t)^{2-1/\alpha}} \sum_{n=1}^{\infty} \Bigg[(-1)^{n-1} \sin(\pi/\alpha)\, \frac{\Gamma(n-1/\alpha)}{\Gamma(\alpha n-1)} \Big(\frac{x^\alpha}{c\Gamma(-\alpha)\,t} \Big)^{n-1} - \sin\Big(\frac{n\pi}{\alpha}\Big) \frac{\Gamma(1+n/\alpha)}{n!} \Big(\frac{x^\alpha}{c\Gamma(-\alpha)\,t} \Big)^{(n+1)/\alpha-1} \Bigg] \tag{2.11}$$

for $t > 0$. *In particular, this yields:*

$$f_{\tau_x}(t) = o(1) \quad \text{as } t \downarrow 0\,; \tag{2.12}$$

$$f_{\tau_x}(t) \sim \frac{x^{\alpha-1}}{\Gamma(\alpha-1)\,\Gamma(1/\alpha)}\, (c\Gamma(-\alpha)\,t)^{-2+1/\alpha} \quad \text{as } t \uparrow \infty\,. \tag{2.13}$$

Proof. It is no restriction to assume below that $c = 1/\Gamma(-\alpha)$ as the general case follows by replacing t in (2.11) with $c\,\Gamma(-\alpha)\,t$ for $t > 0$.

Since X creeps downwards, we can apply the strong Markov property of X at τ_x , use the additive character of X , and exploit the scaling property of X to find

$$\begin{aligned} \mathsf{P}(S_1 > x) &= \mathsf{P}(S_1 > x, X_1 > x) + \mathsf{P}(S_1 > x, X_1 \le x) \\ &= \mathsf{P}(X_1 > x) + \int_0^1 \mathsf{P}(X_1 \le x \,|\, \tau_x = t)\; F_{\tau_x}(dt) \\ &= \mathsf{P}(X_1 > x) + \int_0^1 \mathsf{P}(x + X_{1-t} \le x)\; F_{\tau_x}(dt) \\ &= \mathsf{P}(X_1 > x) + \int_0^1 \mathsf{P}((1-t)^{1/\alpha} X_1 \le 0)\; F_{\tau_x}(dt) \\ &= \mathsf{P}(X_1 > x) + (1/\alpha)\, \mathsf{P}(\tau_x \le 1) \end{aligned} \tag{2.14}$$

where we also use that $\mathsf{P}(X_1 \le 0) = 1/\alpha$ and F_{τ_x} denotes the distribution function of τ_x . Note that the second equality in (2.14) represents a Chapman-Kolmogorov equation of Volterra type (see [11, Section 2] for a formal justification and a brief historical account of the argument). Since $\tau_x =^{\text{law}} x^\alpha\, \tau_1$ by the scaling property of X , we find that (2.14) reads

$$\mathsf{P}(S_1 > x) = \mathsf{P}(X_1 > x) + (1/\alpha)\, F_{\tau_1}(1/x^\alpha) \tag{2.15}$$

for $x > 0$. Hence we see that F_{τ_1} is absolutely continuous (cf. [10] for a general result on the absolute continuity) and by differentiating in (2.15) we get

$$f_{\tau_1}(1/x^\alpha) = x^{1+\alpha} \big[f_{S_1}(x) - f_{X_1}(x) \big] \tag{2.16}$$

for $x > 0$. Letting $t = 1/x^\alpha$ we find that

$$f_{\tau_1}(t) = t^{-1-1/\alpha} \big[f_{S_1}(t^{-1/\alpha}) - f_{X_1}(t^{-1/\alpha}) \big] \tag{2.17}$$

for $t > 0$. Hence (2.11) with $x = 1$ follows by (2.3) and (2.4) above. Moreover, since $\tau_x =^{\text{law}} x^\alpha \tau_1$ we see that $f_{\tau_x}(t) = x^{-\alpha} f_{\tau_1}(tx^{-\alpha})$ and this yields (2.11) with $x > 0$.

It is known that $f_{X_1}(x) \sim c x^{-1-\alpha}$ as $x \to \infty$ (see e.g. (14.34) in [14, p. 88]) and likewise $f_{S_1}(x) \sim c x^{-1-\alpha}$ as $x \to \infty$ (see [1, Corollary 3] and [7] for a proof). From (2.16) we thus see that $f_{\tau_1}(0+) = 0$ and hence $f_{\tau_x}(0+) = 0$ for all $x > 0$ as claimed in (2.12). The asymptotic relation (2.13) follows directly from (2.11) using the reflection formula $\Gamma(1-z)\Gamma(z) = \pi / \sin \pi z$ for $z \in \mathbb{C} \setminus \mathbb{Z}$. This completes the proof. □

Remark 1. Note that (2.14) can be rewritten as follows:

$$(1/\alpha)\,\mathsf{P}(\tau_x > 1) = 1/\alpha + F_{S_1}(x) - F_{X_1}(x) = F_{S_1}(x) - \big(F_{X_1}(x) - F_{X_1}(0)\big) \tag{2.18}$$

for $x > 0$, and from (2.30) in [1] we know that

$$\int_0^\infty e^{-\lambda x} f_{S_1}(x)\, dx = e^{\lambda^\alpha} \int_\lambda^\infty e^{-z^\alpha}\, dz \tag{2.19}$$

for $\lambda > 0$. In view of (2.10) this implies that

$$\int_0^\infty e^{-\lambda x} f_{X_1}(x)\, dx = e^{\lambda^\alpha} - \frac{1}{\alpha} E_{1/\alpha}(\lambda) \tag{2.20}$$

for $\lambda > 0$. Recalling (2.2) we see that (2.20) is equivalent to

$$\int_{-\infty}^0 e^{-\lambda x} f_{X_1}(x)\, dx = \frac{1}{\alpha} E_{1/\alpha}(\lambda) \tag{2.21}$$

for $\lambda > 0$. An explicit series representation for f in place of f_{X_1} in (2.21) was found in [13] (see also [12]) and this expression coincides with (2.3) above when $x < 0$. (Note that (2.21) holds for all $\lambda \in I\!R$ and substitute $y = -x$ to connect to [13].) This represents an analytic argument for the additive factorisation addressed following (2.10) above.

Remark 2. In contrast to (2.12) note that

$$f_{\tau_{(x,\infty)}}(0+) = \frac{c}{\alpha\, x^\alpha} \tag{2.22}$$

for $x > 0$. This is readily derived from $\mathsf{P}(\tau_{(x,\infty)} \le t) = \mathsf{P}(S_t \ge x)$ using $S_t =^{\text{law}} t^{1/\alpha} S_1$ and $f_{S_1}(x) \sim c x^{-1-\alpha}$ for $x \to \infty$ as recalled in the proof above.

Remark 3. If $x < 0$ then applying the same arguments as in (2.14) above with $I_t = \inf_{0 \le s \le t} X_s$ we find that

$$\begin{aligned} \mathsf{P}(I_t \le x) &= \mathsf{P}(I_t \le x, X_t \le x) + \mathsf{P}(I_t \le x, X_t > x) \\ &= \mathsf{P}(X_t \le x) + \int_0^t \mathsf{P}(x + X_{t-s} > x)\, F_{\tau_x}(ds) \\ &= \mathsf{P}(X_t \le x) + (1 - 1/\alpha)\, \mathsf{P}(\tau_x \le t) \end{aligned} \tag{2.23}$$

for $t>0$. In this case, moreover, we also have $\mathsf{P}(I_t \le x) = \mathsf{P}(\tau_x \le t)$ since X creeps through x , so that (2.23) yields

$$\mathsf{P}(\tau_x \le t) = \alpha\, \mathsf{P}(X_t \le x) \tag{2.24}$$

for $x<0$ and $t>0$. Since $X_t =^{\text{law}} t^{1/\alpha} X_1$ this implies

$$f_{\tau_x}(t) = -x\, t^{-1-1/\alpha} F_{X_1}(x t^{-1/\alpha}) = -\sum_{n=1}^{\infty} \frac{\sin(n\pi/\alpha)}{\pi}\, \frac{\Gamma(1+n/\alpha)}{n!}\, \frac{x^n}{t^{1+n/\alpha}} \tag{2.25}$$

for $t>0$ upon using (2.3) above. Replacing t in (2.25) by $c\,\Gamma(-\alpha)\,t$ we get a series representation for f_{τ_x} in the case when $c>0$ is a general constant. The first identity in (2.25) is known to hold in greater generality (see [4] and [2, p. 190] for different proofs).

Remark 4. If $c = 1/2\Gamma(-\alpha)$ and $\alpha \uparrow 2$ then the series representations (2.11) and (2.25) with $t/2$ in place of t reduce to the known expressions for the density function f_{τ_x} of $\tau_x = \inf\{\, t>0 : B_t = x \,\}$ where $B = (B_t)_{t\ge 0}$ is a standard Brownian motion:

$$f_{\tau_x}(t) = \frac{|x|}{\sqrt{2\pi t^3}}\, e^{-x^2/2t} = \frac{|x|}{\sqrt{2\pi t^3}} \sum_{n=0}^{\infty} \frac{(-1)^n}{2^n n!}\, \frac{x^{2n}}{t^n} \tag{2.26}$$

for $t>0$ and $x \in I\!\!R \setminus \{0\}$.

Remark 5. Duality theory for Markov/Lévy processes (see [3, Chap. VI] and [2, Chap. II and Corollary 18 on p. 64]) implies that

$$\mathsf{E} e^{-p\tau_x} = \frac{\int_0^\infty e^{-pt} f_{X_t}(x)\, dt}{\int_0^\infty e^{-pt} f_{X_t}(0)\, dt} \tag{2.27}$$

from where the following identity can be derived (see [2, Lemma 13, p. 230]):

$$\mathsf{P}(\tau_x \le t) = \frac{1}{\Gamma(1-1/\alpha)\,\Gamma(1/\alpha)\, f_{X_1}(0)} \int_0^t \frac{f_{X_s}(x)}{(t-s)^{1-1/\alpha}}\, ds \tag{2.28}$$

for $x \in I\!\!R$ and $t>0$ (being valid for any stable Lévy process). By the scaling property of X we have $f_{X_s}(x) = s^{-1/\alpha} f_{X_1}(x s^{-1/\alpha})$ for $s \in (0,t)$ and $x \in I\!\!R$. Recalling the particular form of the series representation for f_{X_1} given in (2.3), we see that it is not possible to integrate term by term in (2.28) in order to obtain an explicit series representation.

Remark 6. The density function f_{X_1} from (2.3) can be expressed in terms of the Fox functions (see [15]), and the density function f_{S_1} from (2.4) can be expressed in terms of the Wright functions (see [5, Sect. 12] and the references therein). In view of the identity (2.17) and the fact that $f_{\tau_x}(t) = x^{-\alpha} f_{\tau_1}(t x^{-\alpha})$, these facts can be used to provide alternative representations for the density function f_{τ_x} from (2.11) above. We are grateful to an anonymous referee for bringing these references to our attention.

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