Appendix A. Finite versus infinite-activity-Lévy-processes

ndix Finite Infinite

Proposition A.1. *From Rémillard (2013), let L be a Lévy process with characteristics (a, b, k), where k is the Lévy measure defined on $\mathbb{R}$ such that $k(\{0\}) = 0$ and $\int_{\mathbb{R}\setminus 0}\left(1 \wedge |x|^2\right) k(dx) \leq \infty$. In a finite time interval, the number of jumps of Lévy process can be finite or infinite, according as $k(\mathbb{R}) < \infty$ or $k(\mathbb{R}) = \infty$.*

Proposition A.2. *From Rémillard (2013), let L be a Lévy process with characteristics (a, b, k), where k is the Lévy measure defined on $\mathbb{R}$ such that $k(\{0\}) = 0$ and $\int_{\mathbb{R}\setminus 0}\left(1 \wedge |x|^2\right) k(dx) \leq \infty$. A Lévy process has jumps of finite variation if and only if $b = 0$ and $\int_{|x|<1} |x| k(dx) < \infty$.*

Appendix B. Transition tables

Appendix Transition1

B.1. **Transition tables - Merton (1976).** The transition parameters $T^{\nu}_{k,i}$, for $\nu \in \{0, 1, 2\}$, $k \in \{1, \ldots, p\}$, and $i \in \{0, \ldots, p\}$ are

$$T^{\nu}_{k,i} = \sum_{n=0}^{\infty} \mathbb{Q}\left(N_{\Delta t} = n\right)\ \eta^{\nu}_{k}(n) e^{c(n)^2/2} \left[\Phi\left(c_{k,i+1}(n) - c\left(n\right)\right) - \Phi\left(c_{k,i}(n) - c\left(n\right)\right)\right],$$

where $N_{\Delta t}$ is the number of jumps over $[t_m, t_{m+1}]$, $c\left(n\right) = \nu\sigma_n\sqrt{\Delta t}$, and

$$\begin{aligned}
&\mathbb{Q}\left(N_{\Delta t} = n\right) = e^{-\lambda\Delta t}\frac{\left(\lambda\Delta t\right)^n}{n!},\\
&\sigma_n^2 = \sigma^2 + \frac{n}{\Delta t}\delta^2,\\
&\eta_k(n) = a_k e^{\left(r-\bar{d}-\lambda\kappa-\sigma_n^2/2\right)\Delta t + n(\gamma+\delta^2/2)},\\
&c_{k,i}(n) = \frac{\log\left(a_i/a_k\right) - \left(r - \bar{d} - \lambda\kappa - \sigma_n^2/2\right)\Delta t - n(\gamma + \delta^2/2)}{\sigma_n},
\end{aligned}$$

and $\Phi\left(\cdot\right)$ is the standard normal distribution function.

Appendix Transition2

B.2. **Transition tables - Kou (2002).** The transition parameters $T^{\nu}_{k,i}$, for $\nu \in \{0, 1, 2\}$, $k \in \{1, \ldots, p\}$, and $i \in \{0, \ldots, p\}$ are

$$\begin{aligned}
T^0_{k,i} &= \Upsilon(\mu_0, \sigma, \lambda, p_1, \eta_1, \eta_2, x_{i+1}, \Delta t) - \Upsilon(\mu_0, \sigma, \lambda, p_1, \eta_1, \eta_2, x_i, \Delta t),\\
T^1_{k,i} &= \rho^{-1} a_k [\Upsilon(\mu_1, \sigma, \tilde{\lambda}, \tilde{p}_1, \tilde{\eta}_1, \tilde{\eta}_2, x_{i+1}, \Delta t) - \Upsilon(\mu_1, \sigma, \tilde{\lambda}, \tilde{p}_1, \tilde{\eta}_1, \tilde{\eta}_2, x_i, \Delta t)],\\
T^2_{k,i} &= b\rho^{-2} a_k^2 [\Upsilon(\mu_2, \bar{\sigma}, \bar{\lambda}, \bar{p}_1, \bar{\eta}_1, \bar{\eta}_2, \bar{x}_{i+1}, \Delta t) - \Upsilon(\mu_2, 2\sigma, \bar{\lambda}, \bar{p}_1, \bar{\eta}_1, \bar{\eta}_2, \bar{x}_i, \Delta t)],
\end{aligned}$$

where $\mu_0 = r - \frac{1}{2}\sigma^2 - \lambda\kappa, x_i = \log(a_i/a_k), \rho = \exp(-(r-\bar{d})\Delta t), \mu_1 = r+\frac{1}{2}\sigma^2-\lambda\kappa, \tilde{\lambda} = \lambda(1+\kappa), \tilde{p}_1 = p\eta_1/(1+\kappa)(\eta_1-1), \tilde{\eta}_1 = \eta_1-1, \tilde{\eta}_2 = \eta_2+1, \bar{\sigma} = 2\sigma, \bar{\kappa} = p_1(\eta_1/2\bar{\eta}_1)+(1-p_1)(\eta_2/2\bar{\eta}_2)-1, \mu_2 = 2r+\frac{1}{2}\bar{\sigma}^2-\lambda\bar{\kappa}, \bar{\lambda} = \lambda(1+\bar{\kappa}), \bar{\eta}_1 = \eta_1/2-1, \bar{\eta}_2 = \eta_2/2+1, b = \exp(\sigma^2+\lambda(\bar{\kappa}-2\kappa)\Delta t)$, and $\bar{x}_i = x_i - \log(b)$. The function $\Upsilon(.)$ is defined by

$$
\begin{aligned}
\Upsilon\left(\mu,\sigma,\lambda,\eta_1,\eta_2,p_1,x_i,\Delta t\right) &= \frac{e^{(\sigma\eta_1)^2\Delta t/2}}{\sigma\sqrt{2\pi\Delta t}}\sum_{n=1}^{\infty}\pi_n\sum_{k=1}^{n}P_{n,k}\Big(\sigma\sqrt{\Delta t}\eta_1\Big)^k \\
&\times\; I_{k-1}\left(x_i-\mu\Delta t;-\eta_1,-\frac{1}{\sigma\sqrt{\Delta t}},-\sigma\eta_1\sqrt{\Delta t}\right) \\
&+\; \frac{e^{(\sigma\eta_2)^2\Delta t/2}}{\sigma\sqrt{2\pi\Delta t}}\sum_{n=1}^{\infty}\pi_n\sum_{k=1}^{n}Q_{n,k}\Big(\sigma\sqrt{\Delta t}\eta_2\Big)^k \\
&\times\; I_{k-1}\left(x_i-\mu\Delta t;\eta_2,\frac{1}{\sigma\sqrt{\Delta t}},-\sigma\eta_2\sqrt{\Delta t}\right) \\
&+\; \pi_0\Phi\left(-\frac{x_i-\mu\Delta t}{\sigma\sqrt{\Delta t}}\right),
\end{aligned}
$$

and by

$$
\begin{aligned}
&P_{n,k} = \textstyle\sum_{i=k}^{n-1}\begin{pmatrix} n-k-1 \\ i-k \end{pmatrix}\begin{pmatrix} n \\ i \end{pmatrix}.\Big(\dfrac{\eta_1}{\eta_1+\eta_2}\Big)^{i-k}\Big(\dfrac{\eta_2}{\eta_1+\eta_2}\Big)^{n-i}p_1^i p_2^{n-i}, \\
&Q_{n,k} = \textstyle\sum_{i=k}^{n-1}\begin{pmatrix} n-k-1 \\ i-k \end{pmatrix}\begin{pmatrix} n \\ i \end{pmatrix}.\Big(\dfrac{\eta_1}{\eta_1+\eta_2}\Big)^{n-i}\Big(\dfrac{\eta_2}{\eta_1+\eta_2}\Big)^{i-k}p_1^{n-i}p_2^{i}, \\
&I_n\left(c;\alpha,\beta,\delta\right) = \textstyle\int_c^{\infty}e^{\alpha x}Hh_n\left(\beta x-\delta\right)dx,
\end{aligned}
$$

for arbitrary constants α, c, $\beta \in \mathbb{R}$, and $n \in \mathbb{N}$.

Appendix Transition3

B.3. **Transition tables – Variance Gamma - Madan et al. (1998).** From Madan et al. (1998), we define the degenerate hypergeometric function of two variables $\Psi(a,b,\gamma)$ in terms of the modified Bessel function of the second kind $K(.)$ as

$$\begin{aligned}\Psi(a,b,\gamma) = &\frac{c^{\gamma+\frac{1}{2}}\exp(\operatorname{sign}(a)c)(1+u)^{\gamma}}{\sqrt{(2\pi)}\Gamma(\gamma)\gamma}K_{\gamma+\frac{1}{2}}(c)\times\\ &\Phi(\gamma,1-\gamma,1+\gamma;\frac{1+u}{2},-\operatorname{sign}(a)c(1+u))-\\ &\operatorname{sign}(a)\frac{c^{\gamma+\frac{1}{2}}\exp(\operatorname{sign}(a)c)(1+u)^{1+\gamma}}{\sqrt{(2\pi)}\Gamma(\gamma)(1+\gamma)}K_{\gamma-\frac{1}{2}}(c)\times\\ &\Phi(1+\gamma,1-\gamma,2+\gamma;\frac{1+u}{2},-\operatorname{sign}(a)c(1+u))+\\ &\operatorname{sign}(a)\frac{c^{\gamma+\frac{1}{2}}\exp(\operatorname{sign}(a)c)(1+u)^{\gamma}}{\sqrt{(2\pi)}\Gamma(\gamma)\gamma}K_{\gamma-\frac{1}{2}}(c)\times\\ &\Phi(\gamma,1-\gamma,1+\gamma;\frac{1+u}{2},-\operatorname{sign}(a)c(1+u)),\end{aligned}$$

where $c=|a|\sqrt{2+b^2}$, $u=b/\sqrt{2+b^2}$, and where the degenerate hypergeometric function of two variables Φ has the integral representation

$$\Phi\left(\alpha,\beta,\gamma;x,y\right)=\frac{\Gamma\left(\gamma\right)}{\Gamma(\alpha)\Gamma(\gamma-\alpha)}\int_0^1 u^{\alpha-1}(1-u)^{\gamma-\alpha-1}(1-ux)^{-\beta}e^{uy}du.$$

Let $x=\frac{1+u}{2}$, $\lambda=2\operatorname{sign}(a)c$, so that $c=|\lambda|/2$, and set

$$\begin{aligned}\Psi_1\left(x,\lambda,\gamma\right)&=\frac{|\lambda|^{\gamma+\frac{1}{2}}e^{\lambda/2}x^{\gamma}}{2\sqrt{\pi}\Gamma(\gamma)\gamma}K_{\gamma+\frac{1}{2}}\left(c\right)\Phi\left(\gamma,1-\gamma,1+\gamma;x,-\lambda x\right)\\ &=\frac{|\lambda|^{\gamma+\frac{1}{2}}e^{\lambda/2}x^{\gamma}}{2\sqrt{\pi}\Gamma(\gamma)}K_{\gamma+\frac{1}{2}}\left(c\right)\int_0^1 z^{\gamma-1}\left(1-zx\right)^{\gamma-1}e^{-\lambda zx}dz\end{aligned}$$

$$\begin{aligned}\Psi_2\left(x,\lambda,\gamma\right)&=\frac{|\lambda|^{\gamma+\frac{1}{2}}e^{\lambda/2}x^{\gamma+1}}{\sqrt{\pi}\Gamma(\gamma)\left(\gamma+1\right)}K_{\gamma-\frac{1}{2}}\left(c\right)\Phi\left(1+\gamma,1-\gamma,2+\gamma;x,-\lambda x\right)\\ &=\frac{|\lambda|^{\gamma+\frac{1}{2}}e^{\lambda/2}x^{\gamma+1}}{\sqrt{\pi}\Gamma(\gamma)}K_{\gamma-\frac{1}{2}}\left(c\right)\int_0^1 z^{\gamma}\left(1-zx\right)^{\gamma-1}e^{-\lambda zx}dz\end{aligned}$$

$$\Psi_3\left(x,\lambda,\gamma\right)=\frac{|\lambda|^{\gamma+\frac{1}{2}}e^{\lambda/2}x^{\gamma}}{2\sqrt{\pi}\Gamma(\gamma)}K_{\gamma+\frac{1}{2}}\left(c\right)\int_0^1 z^{\gamma-1}\left(1-zx\right)^{\gamma-1}e^{-\lambda zx}dz.$$

If $\lambda > 0$, let $t = \lambda x z$, set

$$\Psi_1\left(x,\lambda,\gamma\right) = \frac{\sqrt{\lambda}e^{\lambda/2}}{2\sqrt{\pi}\Gamma\left(\gamma\right)} K_{\gamma+\frac{1}{2}}\left(\lambda/2\right) \int_0^{\lambda x} t^{\gamma-1}\left(1-\frac{t}{\lambda}\right)^{\gamma-1} e^{-t}dt,$$

and set $I_1\left(x,\lambda,\gamma\right) = \int_0^{\lambda x} t^{\gamma-1}\left(1-\frac{t}{\lambda}\right)^{\gamma-1} e^{-t}dt$. Integrating by parts,

$$\begin{aligned} I_1\left(x,\lambda,\gamma\right) &= \frac{\left(\lambda x\right)^{\gamma}}{\gamma}\left(1-x\right)^{\gamma-1}e^{-\lambda x} + \frac{1}{\gamma}\int_0^{\lambda x} t^{\gamma}\left(1-\frac{t}{\lambda}\right)^{\gamma-1} e^{-t}dt \\ &\quad + \frac{\gamma-1}{\lambda\gamma}\int_0^{\lambda x} t^{\gamma}\left(1-\frac{t}{\lambda}\right)^{\gamma-2} e^{-t}dt. \end{aligned}$$

Set $h_1\left(x,\lambda,\gamma\right) = \int_0^{\lambda x} t^{\gamma}\left(1-\frac{t}{\lambda}\right)^{\gamma-1} e^{-t}dt$ and $h_2\left(x,\lambda,\gamma\right) = \int_0^{\lambda x} t^{\gamma}\left(1-\frac{t}{\lambda}\right)^{\gamma-2} e^{-t}dt$, where h_1 and h_2 are evaluated by Gauss-Legendre quadrature. Then

$$\begin{aligned} \Psi_2\left(x,\lambda,\gamma\right) &= \frac{e^{\lambda/2}}{\sqrt{\pi\lambda}} K_{\gamma-\frac{1}{2}}\left(\lambda/2\right)\int_0^{\lambda x} t^{\gamma}\left(1-\frac{t}{\lambda}\right)^{\gamma-1} e^{-t}dt \\ &= \frac{e^{\lambda/2}}{\sqrt{\pi\lambda}} K_{\gamma-\frac{1}{2}}\left(\lambda/2\right) h_1\left(x,\lambda,\gamma\right), \end{aligned}$$

and $\Psi_3\left(x,\lambda,\gamma\right) = \frac{\sqrt{\lambda}e^{\lambda/2}}{2\sqrt{\pi}\Gamma(\gamma)} K_{\gamma-\frac{1}{2}}\left(\lambda/2\right) I_1\left(x,\lambda,\gamma\right)$, hence

$$\Psi\left(x,\lambda,\gamma\right) = \Psi_1\left(x,\lambda,\gamma\right) - \operatorname{sign}\left(a\right)\Psi_2\left(x,\lambda,\gamma\right) + \operatorname{sign}\left(a\right)\Psi_3\left(x,\lambda,\gamma\right).$$

If $\lambda < 0$, let $t = -\lambda x z$, let

$$\Psi_1\left(x,\lambda,\gamma\right) = \frac{\sqrt{-\lambda}e^{\lambda/2}}{2\sqrt{\pi}\Gamma\left(\gamma\right)} K_{\gamma+\frac{1}{2}}\left(-\lambda/2\right) \int_0^{-\lambda x} t^{\gamma-1}\left(1+\frac{t}{\lambda}\right)^{\gamma-1} e^{t}dt,$$

and set $I_2\left(x,\lambda,\gamma\right) = \int_0^{-\lambda x} t^{\gamma-1}\left(1+\frac{t}{\lambda}\right)^{\gamma-1} e^{t}dt$. Integrating by parts,

$$\begin{aligned} I_2\left(x,\lambda,\gamma\right) &= \frac{\left(-\lambda x\right)^{\gamma}}{\gamma}\left(1-x\right)^{\gamma-1}e^{-\lambda x} - \frac{1}{\gamma}\int_0^{-\lambda x} t^{\gamma}\left(1+\frac{t}{\lambda}\right)^{\gamma-1} e^{t}dt \\ &\quad - \frac{\gamma-1}{\lambda\gamma}\int_0^{-\lambda x} t^{\gamma}\left(1+\frac{t}{\lambda}\right)^{\gamma-2} e^{t}dt. \end{aligned}$$

Set $h_3\left(x,\lambda,\gamma\right) = \int_0^{-\lambda x} t^{\gamma}\left(1+\frac{t}{\lambda}\right)^{\gamma-1} e^{t}dt$ and $h_4\left(x,\lambda,\gamma\right) = \int_0^{-\lambda x} t^{\gamma}\left(1+\frac{t}{\lambda}\right)^{\gamma-2} e^{t}dt$, where h_3 and h_4 are evaluated by Gauss-Legendre quadrature. Then

$$\begin{aligned} \Psi_2\left(x,\lambda,\gamma\right) &= \frac{\sqrt{(-\lambda)}e^{\lambda/2}}{\lambda\sqrt{\pi}\Gamma(\gamma)} K_{\gamma-\frac{1}{2}}\left(-\lambda/2\right) h_3\left(x,\lambda,\gamma\right), \\ \Psi_3\left(x,\lambda,\gamma\right) &= \frac{\sqrt{(-\lambda)}e^{\lambda/2}}{2\sqrt{\pi}\Gamma\left(\gamma\right)} K_{\gamma-\frac{1}{2}}\left(-\lambda/2\right) I_2\left(x,\lambda,\gamma\right). \end{aligned}$$

As a result,

$$\Psi\left(x,\lambda,\gamma\right) = \Psi_1\left(x,\lambda,\gamma\right) - \operatorname{sign}\left(a\right)\Psi_2\left(x,\lambda,\gamma\right) + \operatorname{sign}\left(a\right)\Psi_3\left(x,\lambda,\gamma\right).$$

The transition parameters $T^j_{k,i}$, for $j \in \{0,1,2\}$, $k \in \{1,\ldots,p\}$, and $i \in \{0,\ldots,p\}$ are

$$T^0_{k,i} = \Psi(x_0, \lambda^{(0)}_i, dt/\nu) - \Psi(x_0, \lambda^{(0)}_{i+1}, dt/\nu),$$

$$T^1_{k,i} = \rho^{-1} a_k \Big[\Psi(x_1, \lambda^{(1)}_i, dt/\nu) - \Psi(x_1, \lambda^{(1)}_{i+1}, dt/\nu)\Big],$$

$$T^2_{k,i} = e^{\eta_2} \rho^{-2} a_k^2 \Big[\Psi(x_2, \lambda^{(2)}_i, dt/\nu) - \Psi(x_2, \lambda^{(2)}_{i+1}, dt/\nu)\Big],$$

where $\rho = \exp\{-(r-q)dt\}$, $x_0 = \frac{1+u_0}{2}$, $u_0 = \frac{b_0}{\sqrt{2+b_0^2}}$, $b_0 = \alpha\sqrt{\frac{\nu}{1-\xi_2}}$, $\xi_2 = \frac{\nu\alpha^2}{2}$, $\alpha = \zeta s$, with $\zeta = \frac{\theta}{\sigma^2}$ and $s = \frac{\sigma}{\sqrt{1+\left(\frac{\theta}{\sigma}\right)^2 \frac{\nu}{2}}}$. Thus $\lambda^{(0)}_i = 2\,\mathrm{sign}\,(a_0)c_0$, with $c_0 = |a_0|\,\sqrt{2+b_0^2}$, $a_0 = d_i\sqrt{\frac{1-\xi_2}{\nu}}$, $\xi_1 = \frac{\nu(\alpha+s)^2}{2}$, and

$$d^{(0)}_i = \frac{1}{s}\Big[\ln\left(\frac{a_k}{a_i}\right) + r dt + \frac{dt}{\nu}\ln\left(\frac{1-\xi_1}{1-\xi_2}\right)\Big].$$

Next, $x_1 = \frac{1+u_1}{2}$, $u_1 = \frac{b_1}{\sqrt{2+b_1^2}}$, $b_1 = (\alpha+s)\,\sqrt{\frac{\nu}{1-\xi_1}}$, $\lambda^{(1)}_i = 2\,\mathrm{sign}\,(a_1)c_1$, with $c_1 = |a_1|\,\sqrt{2+b_1^2}$, $a_1 = d^{(0)}_i\sqrt{\frac{1-\xi_1}{\nu}}$.

Further, let $r_2 = 2r$, $\sigma_2 = 2\sigma$, $\theta_2 = 2\theta$, $q_2 = 2q$, $\alpha_2 = \zeta_2 s_2$, with $\zeta_2 = \frac{\theta_2}{\sigma_2^2}$ and $s_2 = \frac{\sigma_2}{\sqrt{1+\left(\frac{\theta_2}{\sigma_2}\right)^2\frac{\nu}{2}}}$. Then $x_2 = \frac{1+u_2}{2}$, $u_2 = \frac{b_2}{\sqrt{2+b_2^2}}$, $b_2 = (\alpha_2+s_2)\,\sqrt{\frac{\nu}{1-\xi^{(2)}_1}}$, with $\xi^{(2)}_1 = \frac{\nu(\alpha_2+s_2)^2}{2}$. Thus, $\lambda^{(2)}_i = 2\,\mathrm{sign}\,(a_2)c_2$, with $c_2 = |a_2|\,\sqrt{2+b_2^2}$, $a_2 = d^{(2)}_i\sqrt{\frac{1-\xi^{(2)}_2}{\nu}}$, $\xi^{(2)}_2 = \frac{\nu\alpha_2^2}{2}$ and

$$d^{(2)}_i = \frac{1}{s_2}\Big[2\ln\left(\frac{a_k}{a_i}\right) + r_2 dt + \eta_2 + \frac{dt}{\nu}\ln\left(\frac{1-\xi^{(2)}_1}{1-\xi^{(2)}_2}\right)\Big],$$

where $\eta_2 = 2w_1 - w_2$, $w_1 = \frac{dt}{\nu}\ln\left(\frac{1-\xi_1}{1-\xi_2}\right)$, and $w_2 = \frac{dt}{\nu}\ln\left(\frac{1-\xi^{(2)}_1}{1-\xi^{(2)}_2}\right)$.

Thus, for $j \geq 3$

$$T^j_{k,i} = e^{\eta_j}\rho^{-j} a_k^j \Big[\Psi(x_j, \lambda^{(j)}_i, dt/\nu) - \Psi(x_j, \lambda^{(j)}_{i+1}, dt/\nu)\Big],$$

where $r_j = jr$, $\sigma_j = j\sigma$, $\theta_j = j\theta$, $q_j = jq$, $\alpha_j = \zeta_j s_j$, with $\zeta_j = \frac{\theta_j}{\sigma_j^2}$ and $s_j = \frac{\sigma_j}{\sqrt{1+\left(\frac{\theta_j}{\sigma_j}\right)^2\frac{\nu}{2}}}$. Hence, $x_j = \frac{1+u_j}{2}$, $u_j = \frac{b_j}{\sqrt{2+b_j^2}}$, $b_j =$

$\big(\alpha_j + s_j\big)\sqrt{\frac{\nu}{1-\xi_1^{(j)}}}$, with $\xi_1^{(j)} = \frac{\nu\big(\alpha_j+s_j\big)^2}{2}$, $\xi_2^{(j)} = \frac{\nu\alpha_j^2}{2}$, and $\lambda_i^{(j)} = 2\,\mathrm{sign}\,\big(a_j\big)c_j$, with $c_j = \big|a_j\big|\sqrt{2+b_j^2}$, $a_j = d_i^{(j)}\sqrt{\frac{1-\xi_2^{(j)}}{\nu}}$, and

$$d_i^{(j)} = \frac{1}{s_j}\left[j\ln\left(\frac{a_k}{a_i}\right) + r_j dt + \eta_j + \frac{dt}{\nu}\ln\left(\frac{1-\xi_1^{(j)}}{1-\xi_2^{(j)}}\right)\right],$$

where $\eta_j = jw_1 - w_j$, $w_1 = \frac{dt}{\nu}\ln\left(\frac{1-\xi_1}{1-\xi_2}\right)$, and $w_j = \frac{dt}{\nu}\ln\left(\frac{1-\xi_1^{(j)}}{1-\xi_2^{(j)}}\right)$.

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