Answers: Lévy-Khintchine formula

April 19, 2024

(1)

WTS: D is the unit ball and

$$\nu(\{0\}) = 0 \text{ and } \int_{\mathbb{R}^d} (|x|^2 \wedge 1)\nu(dx) < \infty, \tag{1}$$

set

$$f(t,x) = (\exp(i\langle t,x\rangle) - 1 - i\langle t,x\rangle I_D(x)). \tag{2}$$

then following function is continuous:

$$t \mapsto \int_{\mathbb{R}^d} f(t,x)\nu(dx). \tag{3}$$

Proof. Take $t_k \to t \implies \sup_{k>0}(t_k) < \infty, \sup_{k>0}(|t_k|^2) < \infty$ (if the supremum is ∞ there exist a subsequence that converges to ∞ which is a contradiction) and

$$\begin{aligned} |f(t_k,x)| &\leq \frac{1}{2}|t_k|^2|x|^2 I_D(x) + 2I_{D^c}(x) && (4)\\ &\leq \frac{1}{2}\sup_k \left(|t_k|^2\right)|x|^2 I_D(x) + 2I_{D^c}(x). && (5) \end{aligned}$$

so $f(t_k,x)$ is dominated (5) which is ν-integrable because of (1). Now by the dominated convergence theorem we have

$$\begin{aligned} &\lim_{k\to\infty}\int_{\mathbb{R}^d} f(t_k,x)\nu(dx) && (6)\\ &= \int_{\mathbb{R}^d} \lim_{k\to\infty} f(t_k,x)\nu(dx) && (7)\\ &= \int_{\mathbb{R}^d} f(t,x)\nu(dx). && (8) \end{aligned}$$

□

(2)

WTS: compound Poisson process has a Lévy-Khintchine representation.

Proof. To see this rewrite the characteristic function of a compound Poisson process X:

$$\phi_X(t) = \exp\left(\lambda \int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle))Q(dx) - 1\right) \tag{9}$$
$$= \exp\left(\lambda \int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1)Q(dx)\right) \tag{10}$$
$$= \exp\left(\int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1)\lambda Q(dx)\right) \tag{11}$$
$$= \exp\left(\int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1 - i\langle t, x\rangle I_D(x) + i\langle t, x\rangle I_D(x))\lambda Q(dx)\right) \tag{12}$$
$$= \exp\left(\int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1 - i\langle t, x\rangle I_D(x))\lambda Q(dx) + i\langle t, \int_D x\lambda Q(dx)\rangle\right) \tag{13}$$

□

(3)

Question: What can you say about the infinitely divisible distribution if ν the Lévy measure is finite?
Answer: The infinitely divisible distribution is the sum of a independent normal distribution and a compound Poisson distribution.

$$\exp\left[-\frac{1}{2}\langle t, At\rangle + i\langle \gamma, t\rangle + \int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1 - i\langle t, x\rangle I_D(x))\,\nu(dx)\right] \tag{14}$$
$$= \exp\left[-\frac{1}{2}\langle t, At\rangle + i\langle \gamma, t\rangle + \int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1)\,\nu(dx) - \int_{\mathbb{R}^d} (i\langle t, x\rangle I_D(x))\,\nu(dx)\right] \tag{15}$$
$$= \exp\left[-\frac{1}{2}\langle t, At\rangle + i\langle \gamma - \int_D x\nu(dx), t\rangle\right] \exp\left[\int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1)\,\nu(dx)\right] \tag{16}$$
$$= \exp\left[-\frac{1}{2}\langle t, At\rangle + i\langle \gamma - \int_D x\nu(dx), t\rangle\right] \exp\left[\int_{\mathbb{R}^d} (\exp(i\langle t, x\rangle) - 1)\,\nu(\mathbb{R}^d)\frac{\nu(dx)}{\nu(\mathbb{R}^d)}\right]. \tag{17}$$

The terms of the product are easily recognized as the characteristic functions of a normal distribution and a compound Poisson distribution.

(4)

WTS:

$$s_k > 0 \to \infty \implies -\frac{1}{2}\langle t, At\rangle + i\langle \gamma, t\rangle s_k^{-1} + \int_{\mathbb{R}^d} \frac{\exp(is_k\langle t, x\rangle) - 1 - is_k\langle t, x\rangle I_D(x)}{s_k^2}\nu(dx) \to \frac{-\langle t, At\rangle}{2}. \tag{18}$$

Proof. Assume $s_k \to \infty$ set

$$f(t, x) = (\exp(i\langle t, x\rangle) - 1 - i\langle t, x\rangle I_D(x)), \tag{19}$$

then all we have to show is that (the second term goes to zero)

$$\int_{\mathbb{R}^d} f(s_k t, x)\nu(dx) \to 0. \tag{20}$$

Use the same dominator (5):

$$\left|\frac{f(s_k t, x)}{s_k^2}\right| \leq \frac{\frac{1}{2}|s_k t|^2|x|^2 I_D(x) + 2I_{D^c}(x)}{s_k^2} \tag{21}$$

$$\leq \frac{1}{2}|t|^2|x|^2 I_D(x) + \frac{2I_{D^c(x)}}{\inf_k s_k^2}. \tag{22}$$

If $\inf_k s_k^2 = 0$ then because $s_k^2 > 0$ there exist a subsequence that converges to 0 which is a contradiction with $s_k > 0 \to \infty$. Again we can apply the dominated convergence theorem:

$$\lim_{k\to\infty} \left| \int_{\mathbb{R}^d} \frac{\exp(is_k\langle t, x\rangle) - 1 - is_k\langle t, x\rangle I_D(x)}{s_k^2} \nu(dx) \right| \tag{23}$$

$$\leq \lim_{k\to\infty} \int_{\mathbb{R}^d} \left| \frac{\exp(is_k\langle t, x\rangle) - 1 - is_k\langle t, x\rangle I_D(x)}{s_k^2} \right| \nu(dx) \tag{24}$$

$$\leq \int_{\mathbb{R}^d} \lim_{k\to\infty} \left| \frac{\exp(is_k\langle t, x\rangle) - 1 - is_k\langle t, x\rangle I_D(x)}{s_k^2} \right| \nu(dx) \tag{25}$$

$$\leq \int_{\mathbb{R}^d} \lim_{k\to\infty} \frac{|\exp(is_k\langle t, x\rangle) - 1 - is_k\langle t, x\rangle I_D(x)|}{s_k^2} \nu(dx) \tag{26}$$

$$\leq \int_{\mathbb{R}^d} \lim_{k\to\infty} \frac{|\exp(is_k\langle t, x\rangle) - 1| + |is_k\langle t, x\rangle I_D(x)|}{s_k^2} \nu(dx) \tag{27}$$

$$\leq \int_{\mathbb{R}^d} \lim_{k\to\infty} \frac{2 + |is_k\langle t, x\rangle I_D(x)|}{s_k^2} \nu(dx) \tag{28}$$

$$\to 0 \tag{29}$$

□