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Abelian theorems for stochastic volatility models with application to the estimation of jump activity of volatility

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Abstract

In this paper, we prove a kind of Abelian theorem for a class of stochastic volatility models (X, V), where both the state process X and the volatility process V may have jumps. Our results relate the asymptotic behavior of the characteristic function of X_Δ for some $\Delta > 0$ in a stationary regime to the Blumenthal-Getoor indexes of the Lévy processes driving the jumps in X and V. The results obtained are used to construct consistent estimators for the above Blumenthal-Getoor indexes based on low-frequency observations of the state process X. We derive the convergence rates for the corresponding estimator and show that these rates can not be improved in general.

Contents

1 Introduction

Consider a class of *affine stochastic volatility* (ASV) models with jumps both in the state process and in the volatility of the form:

$$dX_t = (a_X + b_X V_{t-})dt + \sqrt{V_{t-}}\, dW_{1,t} + dZ_{1,t}, \tag{1}$$

$$dV_t = (a_V - b_V V_{t-})dt + a_V \sigma \sqrt{V_{t-}}\, dW_{2,t} + dZ_{2,t}, \tag{2}$$

where $(W_{1,t}, W_{2,t})$ is a two-dimensional Wiener process such that $\mathrm{corr}(W_{1,t}, W_{2,t}) = \rho$, $(Z_{1,t}, Z_{2,t})$ is a two-dimensional pure jump Lévy process with an increasing or constant $Z_{2,t}$, a_X, b_X are two real numbers, b_V, σ are two positive real numbers, and $a_V \geq 0$. ASV models have got much attention in the past decade (see Keller-Ressel, 2008 for an overview). Such well-known stochastic volatility models as Heston, 1993, Bates, 1996 and Barndorff-Nielsen and Shephard, 2001 models are in the class of ASV models, and this fact allows to treat all of them within one theoretical framework. The main reason for the popularity of ASV models is their analytic tractability: the conditional characteristic function of the vector (X_t, V_t) given (X_0, V_0) has, for any $t > 0$, an exponentially affine structure in (X_0, V_0) and can be efficiently computed via solving a system of ordinary differential equations. Various analytical properties of ASV models such as ergodicity or the existence of moments have been extensively studied in the literature (see, e.g., Glasserman and Kim, 2010 and Keller-Ressel, 2011 for the most recent results). In this respect one contribution of the current paper is the derivation of the so-called Abelian theorem relating the asymptotic behavior of the characteristic function of X_t for any $t > 0$ to the asymptotic behavior of the Lévy measure of the two-dimensional Lévy process (Z_1, Z_2) at the point $(0, 0)$. The latter behavior is closely connected to the notion of a Blumenthal-Getoor index which is the main object of our study. For a one-dimensional Lévy process $Z = (Z_t)_{t \geq 0}$ with a Lévy measure ν, the Blumenthal-Getoor index of Z is defined as

$$\mathtt{BG}(Z) = \inf\left\{ r > 0 : \int_{|x| \leq 1} |x|^r \nu(dx) < \infty \right\}.$$

The Blumenthal-Getoor (BG) index is a fundamental characteristic of the Lévy process Z that determines the activity of jumps in Z. If $\nu([-\varepsilon, \varepsilon]) < \infty$, then the process Z has finite activity of jumps and $\mathtt{BG}(Z) = 0$. If the Lévy measure $\nu((-\infty, -\varepsilon] \cup [\varepsilon, \infty))$ diverges near $\varepsilon = 0$ at a rate $\varepsilon^{-\alpha}$ for some $\alpha > 0$, then the BG index of Z is equal to α. From a practical point of view, the importance of the Blumenthal-Getoor index lies in the fact that it determines the smoothness properties of the marginal density of Z and has significant impact on the convergence of different approximation algorithms for Z (see, e.g., Dereich, 2011). One of the main results of our study states that the c.f. $\phi_\Delta(u)$ of the increments $X_{t+\Delta} - X_t$ for some $\Delta > 0$ in a stationary regime has a representation

$$\log|\phi_\Delta(u)| = -\tau_1 u - \tau_2 u^\alpha (1 + r(u)), \quad |r(u)| \leq \tau_3 u^{-\varkappa}, \quad u > 1 \tag{3}$$

with some constants $\tau_1 \geq 0$, $\tau_2 > 0$, $\tau_3 \geq 0$, $\varkappa > 0$ and $\alpha \geq 0$ depending on the parameters of the model (1)-(2). The representation (3) reveals the essential difference in the asymptotic behavior of $\phi_\Delta(u)$ between the case of Heston-like ASV models ($a_V > 0$) and the case of Barndorff-Nielsen-Shephard-like ASV models ($a_V = 0$). While in the first case the asymptotic behavior of $\log|\phi_\Delta(u)|$ is equivalent to $-\tau_1 u$, in the second case $\log|\phi_\Delta(u)|$ behaves like $-\tau_2 u^\alpha$ as u tends to infinity, where α is proportional to the maximum of BG indexes of the Lévy processes Z_1 and Z_2.

The representation (3) is not only of theoretical interest, it can be used to construct statistical procedures for estimating the Blumenthal-Getoor indexes of the Lévy processes Z_1 and Z_2. Recently, the problem of estimation of the BG index from the discrete observations of the Lévy process Z or some other processes based on Z has drawn much attention in the literature. Aït-Sahalia and Jacod, 2009, studied the problem of estimating the so called jump activity index that is defined for any Itô semimartingale X via

$$\mathtt{JAI}(X) = \inf\left\{ r > 0 : \sum_{0 \le s \le T} |\Delta X_s|^r < \infty \right\},$$

where $\Delta X_s = X_s - X_{s-}$ is the size of the jump at time s and T is a fixed time horizon. Note that $\mathtt{JAI}(X)$ is a random quantity, which is to be determined pathwise. In the case of a Lévy process X, $\mathtt{JAI}(X)$ coincides with the Blumenthal-Getoor index. Obviously, one can compute $\mathtt{JAI}(X)$ if the whole path of the process X up to time T is observed. In a more realistic situation when the process X is observed on the discrete grid $\{0, \Delta, \ldots, \Delta n\}$ with $\Delta n = T$ and $\Delta \to 0$ as $n \to \infty$ (*high-frequency* data), Aït-Sahalia and Jacod proposed a method which is able to consistently estimate $\mathtt{JAI}(X)$ and is based on the statistics that counts the "big" increments of the process X. Turning to the case of *low-frequency* data, i.e., the case of fixed $\Delta > 0$ and $T \to \infty$, one may wonder if any kind of statistical inference is possible in this situation at all. Indeed, one challenge is that the transition density of X in ASV models is hardly ever known in closed form making the maximum-likelihood estimation difficult. Furthermore, the volatility process V is not directly observable leading to a kind of filtering problem which requires the elimination of V. The latter filtering problem is well understood in the case of high-frequency data and poses significant problems if Δ does not tend to 0. The first results showing that a consistent estimation of the BG index based on low-frequency data is possible, were obtained in Belomestny, 2010 for the case of Lévy processes. The inference in Belomestny, 2010 relied on the kind of Abelian theorem that characterizes the decay of the c.f. of a Lévy process Z. Such Abelian theorems are well known in the literature: Bismut, 1983 showed that the tail integral $\nu\big((-\infty, -x) \cup (x, +\infty)\big)$ behaves asymptotically like $c_1 x^{-\gamma}$ as $x \to +\infty$ if and only if the characteristic exponent of a Lévy process Z with the Lévy measure ν behaves like $-c_2|u|^\gamma$ as $|u| \to \infty$ (here c_1, c_2, and γ are positive numbers). It turns out that the ideas similar to ones in Belomestny, 2010 can be used to construct estimates for the BG indexes in the model (1)-(2) and the representation (3) plays a crucial role in this construction.

The paper is organized as follows. In Section 2, we establish and discuss the representation (3). The estimation algorithm for the BG of Z_2 is formulated and analyzed in Section 3. In particular, we derive the convergence rates for the proposed estimate and discuss their optimality. Section 4 contains the proofs. Some important properties of the ASV model are collected in Appendix A.

2 Abelian theorem

Denote by ν_1 and ν_2 the Lévy measures of the Lévy processes Z_1 and Z_2, respectively. Assume that the following asymptotic relations hold

(AN1)

$$\varepsilon^{\gamma_1} \int_{|x|>\varepsilon} \nu_1(dx) \quad = \quad \beta_{0,1} + \beta_{1,1}\varepsilon^{\chi_1}(1 + O(\varepsilon)), \quad \varepsilon \to +0,$$

(AN2)

$$\varepsilon^{\gamma_2} \int_{y>\varepsilon} \nu_2(dy) \quad = \quad \beta_{0,2} + \beta_{1,2}\varepsilon^{\chi_2}(1 + O(\varepsilon)), \quad \varepsilon \to +0$$

with some $0 < \gamma_1, \gamma_2 \leq 1$, $\beta_{0,1} > 0, \beta_{0,2} > 0$ and $0 \leq \chi_1 < \gamma_1, 0 \leq \chi_2 < \gamma_2$. The assumptions (AN1) and (AN2) imply that the Blumenthal-Getoor indexes of the Lévy processes Z_1 and Z_2 are equal to γ_1 and γ_2, respectively. Moreover, suppose that

(AE)

$$b_V > 0, \quad a_V \sigma^2 < 2,$$

(AM)

$$\int_{|x|>1} |x|^{2+\delta} \nu_2(dx) < \infty.$$

The conditions (AE) and (AM) ensure the existence and uniqueness of the solution of (2) together with the positive recurrence on $(0, \infty)$ (see Masuda, 2007). As a result, V admits a unique invariant distribution π and $V_t > 0$ almost surely, for all $t > 0$. If additionally V_0 is taken to have the distribution π, then V_t is strictly stationary with the stationary distribution π. Then the strict stationarity of V implies the strict stationarity of the process $(X_{t+\Delta} - X_t)_{t \geq 0}$ for any $\Delta > 0$. Denote by ϕ_Δ the characteristic function of $X_{t+\Delta} - X_t$ in a stationary regime. The following theorem describes the asymptotic behavior of $\phi_\Delta(u)$ as $|u| \to \infty$.

Theorem 2.1. *Assume that the assumptions (AN1), (AN2), (AE) and (AM) are fulfilled. Then*

$$\log |\phi_\Delta(u)| = -\tau_1 u - \tau_2 u^\alpha (1 + r(u)), \quad |r(u)| \leq \tau_3 u^{-\varkappa}, \quad u > 1, \tag{4}$$

where $\tau_1 \geq 0$, $\tau_2 > 0$, $\tau_3 \geq 0$, $\alpha \geq 0$ and $\varkappa > 0$ are some numbers depending on the parameters of the model (1)-(2)*. In particular,*

- *if* $a_V > 0$, *then* τ_1 *is positive,* $\alpha = \max\{\gamma_1, \gamma_2\}$, *and*

$$\varkappa = \begin{cases} (\gamma_2 - \gamma_1) \wedge \chi_1, & \textit{if } \gamma_1 < \gamma_2, \\ (\gamma_1 - \gamma_2) \wedge \chi_2, & \textit{if } \gamma_1 > \gamma_2, \\ \chi_1 \wedge \chi_2, & \textit{if } \gamma_1 = \gamma_2; \end{cases}$$

- *if* $a_V = 0$, *then* $\tau_1 = 0$, $\alpha = \max\{\gamma_1, 2\gamma_2\}$, *and*

$$\varkappa = \begin{cases} (2\gamma_2 - \gamma_1) \wedge 2\chi_2 \wedge 1, & \textit{if } \gamma_1 < 2\gamma_2, \\ (\gamma_1 - 2\gamma_2) \wedge \chi_1, & \textit{if } \gamma_1 > 2\gamma_2, \\ \chi_1 \wedge 2\chi_2 \wedge 1, & \textit{if } \gamma_1 = 2\gamma_2. \end{cases}$$

Discussion It is easily seen that $\tau_1 > 0$ as long as $a_V > 0$ and $\tau_1 = 0$ if $a_V = 0$, meaning that the asymptotic behavior of $\phi_\Delta(u)$ changes markedly if we move from the Heston-like ASV models ($a_V > 0$) to the Barndorf-Nielsen-Shephard-like ASV models ($a_V = 0$). Furthermore, if $\gamma_2 \geq \gamma_1$ then the value of α is always proportional to the BG index of Z_2. Hence, in the latter case the problem of statistical inference on γ_2 can be reformulated as the problem of estimating α in (4), which is considered in the next section.

3 Estimation of the Blumenthal-Getoor index

Suppose that the discrete observations $X_0, X_\Delta, \ldots, X_{n\Delta}$ of the state process X are available for some fixed $\Delta > 0$. First, estimate $\phi_\Delta(u)$ by its empirical counterpart $\phi_n(u)$ defined as

$$\phi_n(u) = \frac{1}{n} \sum_{k=1}^{n} e^{\mathrm{i}u(X_{\Delta k} - X_{\Delta(k-1)})}. \tag{5}$$

Note that under the assumptions (AE) and (AM),

$$\frac{1}{n} \sum_{k=1}^{n} e^{\mathrm{i}u(X_{\Delta k} - X_{\Delta(k-1)})} \xrightarrow{a.s.} \phi_\Delta(u), \quad n \to \infty$$

by the Birkhoff's ergodic theorem (see, e.g., Athreya and Lahiri, 2010). Fix some $\theta > 2$ such that $2\theta \in \mathbb{N}$ and consider a random function

$$\mathcal{Y}_n(u) = \log\left\{-\log\left[|\phi_n(u)|^{2\theta} / |\phi_n(\theta u)|^2\right]\right\}.$$

Furthermore, introduce a weighting function $w^{U_n}(u) = U_n^{-1} w^1(u/U_n)$, where U_n is a sequence of positive numbers tending to infinity, the function w^1 is supported on $[\varepsilon, 1]$ and satisfy

$$\int_\varepsilon^1 w^1(u)\, du = 0, \quad \int_\varepsilon^1 w^1(u) \log u\, du = 1. \tag{6}$$

Next, define an estimate of the parameter α in (4) by

$$\alpha_n = \int_0^\infty w^{U_n}(u)\mathcal{Y}_n(u)\,du. \tag{7}$$

The estimate (7) can be alternatively defined as $\alpha_n = l_{n,1}$ with

$$(l_{n,0}, l_{n,1}) := \underset{(l_0,l_1)}{\operatorname{argmin}} \int_0^{U_n} w_\diamond^{U_n}(u)(\mathcal{Y}_n(u) - l_1\log(u) - l_0)^2\,du,$$

where $w_\diamond^{U_n}(u)$ is a suitable weighting function supported on $[\varepsilon U_n, U_n]$. In order to see that α_n is a reasonable estimate of α, we introduce a deterministic quantity

$$\bar{\alpha}_n = \int_0^\infty w^{U_n}(u)\mathcal{Y}(u)\,du$$

with

$$\mathcal{Y}(u) := \log\left\{-\log\left[|\phi(u)|^{2\theta}/\,|\phi(\theta u)|^2\right]\right\} = \log(2\tau_\theta u^\alpha R(u)),$$

where by Theorem 2.1 we have $\tau_\theta = \tau_2(\theta - \theta^\alpha)$ and $R(u) \to 1$ as $u \to +\infty$. Using Theorem 2.1 one can also show (see Lemma 5.4) that for n large enough,

$$|\alpha - \bar{\alpha}_n| \le C_1\,\tau_3\,U_n^{-\varkappa}, \tag{8}$$

with some constant C_1 not depending on the parameters of the underlying ASV model. Hence, α is close to $\bar{\alpha}_n$ in the sense of (8); the next theorem shows that $\bar{\alpha}_n$ converges to α_n in probability.

Theorem 3.1. *Consider a class of ASV models of the form* (1)-(2) *such that the assumptions (AN1), (AN2), (AM) and (AE) are fulfilled. If* $a_V > 0$ *(*$\tau_1 > 0$*) and the sequence* U_n *fulfills*

$$\varepsilon_{1,n} := \frac{\log n}{\sqrt{n}}\, e^{2\theta(\tau_1+\tau_2+\tau_2\tau_3)U_n} \to 0, \quad U_n \to \infty, \quad n \to \infty,$$

then

$$\mathrm{P}\left\{|\alpha_n - \bar{\alpha}_n| > C_2\frac{\varepsilon_{1,n}}{\tau_\theta U_n^\alpha}\right\} \le C_3 n^{-1-\delta} \tag{9}$$

for some constants $C_2 > 0$, $C_3 > 0$ *and* $\delta > 0$ *not depending on* α, τ_1, τ_2 *and* τ_3. *In the case* $a_V = 0$ *(*$\tau_1 = 0$*) we get*

$$\mathrm{P}\left\{|\alpha_n - \bar{\alpha}_n| > C_2\frac{\varepsilon_{2,n}}{\tau_\theta U_n^\alpha}\right\} \le C_3 n^{-1-\delta},$$

provided

$$\varepsilon_{2,n} := \frac{\log n}{\sqrt{n}}\, e^{2\theta(\tau_2+\tau_2\tau_3)U_n^\alpha} \to 0, \quad U_n \to \infty, \quad n \to \infty.$$

Denote by $\mathcal{A}_H$ a class of ASV models (1) such that a_V is strictly positive, assumptions (AN1), (AN2), (AM) and (AE) are fulfilled, and additionally

$$\min\{\tau_1, \tau_2\} \geq \underline{\tau} > 0, \quad \tau_3 \leq \bar{\tau} < \infty, \quad 0 < \alpha \leq \bar{\alpha}, \quad 0 < \varkappa \leq \bar{\varkappa} \tag{10}$$

in the representation (4). As we will see in the proof of Theorem 2.1, all conditions in (10) can be reformulated in terms of the parameters of the underlying ASV model (1)-(2). Combining (8) with (9) and choosing U_n in an optimal way, we arrive at

$$\sup_{(X,V)\in\mathcal{A}_H} \mathrm{P}_{(X,V)}\left(|\alpha-\alpha_n| > C_4 \log^{-\bar{\varkappa}} n\right) \leq C_5 n^{-1-\delta}, \tag{11}$$

where constants C_4 and C_5 depend on $\underline{\tau}$, $\bar{\tau}$ and $\bar{\alpha}$ only. Since

$$\sum_{n=1}^{\infty} \mathrm{P}_{(X,V)}\{|\alpha-\alpha_n| > C_4 \log^{-\bar{\varkappa}} n\} \leq C_5 \sum_{n=1}^{\infty} n^{-1-\delta} < \infty,$$

for any $(X, V) \in \mathcal{A}_H$, it follows by Borel-Cantelli lemma that the upper bound of the sequence of events $\{|\alpha-\alpha_n| > C_4 \log^{-\bar{\varkappa}} n\}$, $n \in \mathbb{N}$, is of probability 0, i.e.,

$$\mathrm{P}_{(X,V)}\left\{|\alpha-\alpha_n| > C_4 \log^{-\bar{\varkappa}} n \text{ for infinitely many n}\right\} = 0,$$

or, equivalently,

$$\mathrm{P}_{(X,V)}\left\{\overline{\lim_{n\to\infty}}\left(\log^{\bar{\varkappa}} n\, |\alpha-\alpha_n|\right) > C_4\right\} = 0.$$

In the case $a_V = 0$, i.e., $\tau_1 = 0$ in (4), one can define a class $\mathcal{A}_{BNS}$ with

$$\tau_2 \geq \bar{\tau} > 0, \quad \tau_3 \leq \bar{\tau} < \infty \quad 0 < \alpha \leq \bar{\alpha}, \quad 0 < \varkappa \leq \bar{\varkappa} \tag{12}$$

to get

$$\sup_{(X,V)\in\mathcal{A}_{OU}} \mathrm{P}_{(X,V)}\left(|\alpha-\alpha_n| > C_4 \log^{-\bar{\varkappa}/\bar{\alpha}} n\right) \leq C_5 n^{-1-\delta}. \tag{13}$$

Discussion As can be seen, the rates of convergence of α_n are logarithmic and depend on the upper bound $\bar{\alpha}$ for the BG index α. The latter feature can also be observed in the high-frequency setup of Aït-Sahalia and Jacod, 2009. Comparing the first part of Theorem 3.1 with the situation where the Lévy process Z_2 is observed directly (see Belomestny, 2010, Theorem 6.7), we immediately realize that the convergence rates in both cases are of the same order, indicating that the problem of estimating the BG index of Z_2 from the low-frequency observations of the process X has the same complexity as the similar problem based on direct observations of the Lévy process Z_2. Moreover, under the presence of a nonzero Gaussian part the latter estimation problem becomes even more complex than the former one, as far as the rates of convergence are concerned. The results of Belomestny, 2010 (Theorem 6.5) also indicate that the convergence rates in (11) and (13) are optimal and can not be improved in general.

4 Proofs

4.1 Proof of Theorem 2.1

It follows from the general results on affine processes (see, e.g., Duffie, Filipović and Schachermayer, 2003) that for any $s \leq t$

$$\begin{aligned} \phi(u, w, t-s|x, v) &= \mathbb{E}\left[e^{\mathrm{i}uX_t + \mathrm{i}wV_t} | X_s = x, V_s = v\right] \\ &= \exp\left\{\psi_0(u, w, t-s) + \mathrm{i}xu + v\psi_1(u, w, t-s)\right\}, \quad (u, v) \in \mathbb{R} \times \mathbb{R}_{\geq 0}, \end{aligned} \tag{14}$$

where $\psi_0(u, w, t)$ and $\psi_1(u, w, t)$ are some complex-valued functions satisfying the system of non-linear differential equations

$$\begin{cases} \frac{\partial \psi_1(u,w,t)}{\partial t} &= \sigma^2 a_V^2 \psi_1^2(u, w, t) + (2 \cdot \mathrm{i}\, a_V \sigma \rho u - b_V)\, \psi_1(u, w, t) - (u^2 - \mathrm{i}\, b_X u), \\ \frac{\partial \psi_0(u,w,t)}{\partial t} &= \mathrm{i}\, a_X u + a_V \psi_1(u, w, t) + \int_{-\infty}^{\infty} \int_0^{\infty} \left(e^{\mathrm{i}ux + \psi_1(u,w,t)y} - 1\right) \nu(dx, dy) \end{cases} \tag{15}$$

with the initial conditions

$$\psi_1(u, w, 0) = \mathrm{i}w, \qquad \psi_0(u, w, 0) = 0.$$

The following lemma easily follows from the standard results on ODEs.

Lemma 4.1. *The solution of the equation*

$$\frac{\partial \psi(w, s)}{\partial s} = \Phi(\psi(w, s)), \quad \psi(w, 0) = \mathrm{i}w \tag{16}$$

with

$$\Phi(z) = Az^2 + Bz - C,$$

where A, B and C are complex numbers is explicitly given by the formula

$$\psi(w, s) = -\frac{2C(\exp(\lambda s) - 1) - (\lambda(\exp(\lambda s) + 1) + B(\exp(\lambda s) - 1))(\mathrm{i} \cdot w)}{\lambda(\exp(\lambda s) + 1) - B(\exp(\lambda s) - 1) - 2A(\exp(\lambda s) - 1)(\mathrm{i} \cdot w)},$$

where $\lambda = \sqrt{B^2 + 4AC}$.

Lemma 4.1 implies that

$$\psi_1(u, w, s) = -\frac{2C(\exp(\lambda s) - 1) - (\lambda(\exp(\lambda s) + 1) + B(\exp(\lambda s) - 1))(\mathrm{i} \cdot w)}{\lambda(\exp(\lambda s) + 1) - B(\exp(\lambda s) - 1) - 2A(\exp(\lambda s) - 1)(\mathrm{i} \cdot w)} \tag{17}$$

with

$$A = \sigma^2 a_V^2, \quad B = 2 \cdot \mathrm{i}\, a_V \sigma \rho u - b_V, \quad C = u^2 - \mathrm{i}\, b_X u, \quad \lambda = \sqrt{B^2 + 4AC},$$

and

$$\psi_0(u,w,t) = \mathrm{i}\, a_X ut + a_V \int_0^t \psi_1(u,w,s)\, ds \\ + \int_0^t \left[\int_{-\infty}^{\infty} \int_0^{\infty} \Big(\exp\big\{ \mathrm{i}\, ux + \psi_1(u,w,s)y \big\} - 1 \Big) \nu(dx,dy) \right] ds. \tag{18}$$

Under assumptions (AE) and (AM), the process $(V_t)_{t \geq 0}$ and, consequently, $(X_{t+\Delta} - X_t)_{t \geq 0}$ is ergodic. Due to (14), the c.f. of the increments $X_{t+\Delta} - X_t$ in a stationary regime is given by

$$\phi_\Delta(u) = \mathbb{E}_\pi \left[e^{\mathrm{i}u(X_{t+\Delta} - X_t)} \right] = e^{\psi_0(u,0,\Delta)} \mathbb{E}_\pi \left[e^{V_t \psi_1(u,0,\Delta)} \right] = \exp \left\{ \psi_0(u,0,\Delta) + l(\psi_1(u,0,\Delta)) \right\},$$

where π is the invariant distribution of the volatility process V and l is the Laplace exponent of π, i.e.,

$$l(w) = \log \left[\int_0^\infty e^{wy}\, \pi(dy) \right] = \lim_{t \to \infty} \psi_0(0, -\mathrm{i}w, t).$$

As a result,

$$l(w) = a_V \int_0^\infty \psi_1(0, -\mathrm{i}w, s) ds + \int_0^\infty \left[\int_0^\infty \Big(e^{\psi_1(0,-\mathrm{i}w,s)y} - 1 \Big) \nu_2(dy) \right] ds. \tag{19}$$

Our objective is now to infer on the asymptotic behavior of the function

$$\log |\phi_\Delta(u)| \quad = \quad \mathrm{Re} \left\{ \psi_0(u,0,\Delta) \right\} + \mathrm{Re} \left\{ l(\psi_1(u,0,\Delta)) \right\} \tag{20}$$

as $u \to +\infty$, where ψ_1 is given by (17), ψ_0 - by (18), and l is in the form (19). Consider now two cases.

Case $\mathbf{a_V = 0}$. We have $A = 0,\ B = -b_V,\ \lambda = b_V$, and formula (17) boils down to

$$\psi_1(u,w,s) \quad = \quad \frac{C}{b_V}(\exp(-b_V s) - 1) + (\mathrm{i} \cdot w) \exp(-b_V s).$$

Hence

$$\begin{aligned} \psi_1(0,w,s) &= \mathrm{i}e^{-b_V s} w, \\ \psi_1(u,0,s) &= B_s C = B_s(u^2 - \mathrm{i}b_X u) \end{aligned}$$

with $B_s = b_V^{-1}(\exp(-b_V s) - 1)$. Moreover,

$$l(w) = \int_0^\infty \left[\int_0^\infty \left(e^{e^{-b_V s} wy} - 1 \right)\ \nu_2(dy) \right] ds,$$

and

$$\psi_0(u,0,\Delta) = \mathrm{i}a_X u\Delta + \int_0^\Delta \left[\int_{-\infty}^\infty \int_0^\infty \left(e^{\mathrm{i}ux + B_\Delta(u^2 - \mathrm{i}b_X u) e^{-b_V s} y} - 1 \right) \nu(dx,dy) \right]\ ds.$$

Formula (20) yields

$$\begin{aligned}\log|\phi_\Delta(u)| &= \operatorname{Re}\left\{\int_0^\Delta \left[\int_{-\infty}^{\infty}\int_0^\infty \left(e^{\mathrm{i}ux+B_\Delta(u^2-\mathrm{i}b_X u)e^{-b_V s}y}-1\right)\nu(dx,dy)\right] ds\right\}\\ &\quad+\operatorname{Re}\left\{\int_0^\infty \left[\int_0^\infty \left(e^{e^{-b_V s}B_\Delta\left(u^2-\mathrm{i}b_X u\right)y}-1\right)\ \nu_2(dy)\right] ds\right\}\\ &=: W_1+W_2.\end{aligned}$$

In what follows we derive asymptotic expansions (as $u\to+\infty$) for the terms W_1 and W_2. Set $c_\gamma=\Gamma(1-\gamma)$, $d_\gamma=\Gamma(1-\gamma)\sin\left((1-\gamma)\pi/2\right)$, and $e_\gamma=\Gamma(1-\gamma)\cos\left((1-\gamma)\pi/2\right)$ for any $\gamma\in\mathbb{R}$. For estimating the term W_1 we apply Lemma 5.3 with $\varrho=-B_\Delta e^{-b_V s}u^2$ and $\phi=-B_\Delta b_X e^{-b_V s}u$ to get

$$W_1=-\int_0^\Delta \Big[\beta_{0,2}c_{\gamma_2}\varrho^{\gamma_2}\left[1+\mathcal{R}_1(\varrho,\phi)\right]+\mathcal{R}(u)\Big]ds+O(1),\quad u\to+\infty,$$

where $\mathcal{R}_1(\varrho,\phi)=\bar{A}\varrho^{-\chi_2}\beta_{1,2}/\beta_{0,2}+\phi/\varrho$, $\mathcal{R}(u)=-u^{\gamma_1}\Big(\beta_{0,1}d_{\gamma_1}+\beta_{1,1}d_{\gamma_1-\chi_1}u^{-\chi_1}\Big)$ and $\bar{A}$ is some constant not depending on the parameters of the model (1)-(2) and Δ. This gives the expansion

$$W_1 = -\delta_{1,1}^{(1)}u^{\gamma_1}-\delta_{2,1}^{(1)}u^{\gamma_1-\chi_1}-\delta_{1,2}^{(1)}u^{2\gamma_2}-\delta_{2,2}^{(1)}u^{2\gamma_2-2\chi_2}-\delta_{3,2}^{(1)}u^{2\gamma_2-1}+O(1),\quad u\to+\infty$$

with the coefficients

$$\begin{aligned}\delta_{1,1}^{(1)} &= \beta_{0,1}d_{\gamma_1}\Delta,\\ \delta_{2,1}^{(1)} &= \beta_{1,1}d_{\gamma_1-\chi_1}\Delta,\\ \delta_{1,2}^{(1)} &= u^{-2\gamma_2}\int_0^\Delta \beta_{0,2}c_{\gamma_2}\varrho^{\gamma_2}ds=\beta_{0,2}c_{\gamma_2}(-B_\Delta)^{\gamma_2}\int_0^\Delta e^{-b_V s\gamma_2}ds\\ &= \beta_{0,2}c_{\gamma_2}(-B_\Delta)^{\gamma_2}\frac{1-e^{-b_V\Delta\gamma_2}}{b_V\gamma_2},\\ \delta_{2,2}^{(1)} &= u^{-2(\gamma_2-\chi_2)}\int_0^\Delta c_{\gamma_2}\bar{A}\beta_{1,2}\varrho^{\gamma_2-\chi_2}ds=c_{\gamma_2}\bar{A}\beta_{1,2}\left(-B_\Delta\right)^{\gamma_2-\chi_2}\frac{1-e^{-b_V\Delta(\gamma_2-\chi_2)}}{b_V(\gamma_2-\chi_2)},\\ \delta_{3,2}^{(1)} &= b_X\delta_{1,2}^{(1)}.\end{aligned}$$

Turn now to W_2. Making use of Lemma 5.1 with $\phi=-e^{-b_V s}B_\Delta b_X u$ and $\varrho=-e^{-b_V s}B_\Delta u^2$, we arrive at the asymptotic formula

$$W_2 = -\int_0^\infty \varrho^{\gamma_2}\Big[\beta_{0,2}c_{\gamma_2}\left(1+(\phi/\varrho)\right)+\beta_{1,2}c_{\gamma_2-\chi_2}\varrho^{-\chi_2}\Big]ds+O(1),\quad u\to+\infty \tag{21}$$

or, equivalently,

$$W_2 = -\delta_{1,2}^{(2)}u^{2\gamma_2}-\delta_{2,2}^{(2)}u^{2\gamma_2-2\chi_2}-\delta_{3,2}^{(2)}u^{2\gamma_2-1}+O(1), \tag{22}$$

where

$$
\begin{aligned}
\delta_{1,2}^{(2)} &= u^{-2\gamma_2}\beta_{0,2}c_{\gamma_2}\int_0^\infty \varrho^{\gamma_2}ds = \frac{\beta_{0,2}c_{\gamma_2}}{\gamma_2 b_V}\,(-B_\Delta)^{\gamma_2}\,,\\
\delta_{2,2}^{(2)} &= u^{-2\gamma_2+2\chi_2}\beta_{1,2}c_{\gamma_2-\chi_2}\int_0^\infty \varrho^{\gamma_2-\chi_2}ds = \frac{\beta_{1,2}c_{\gamma_2-\chi_2}}{(\gamma_2-\chi_2)b_V}\,(-B_\Delta)^{\gamma_2-\chi_2}\,,\\
\delta_{3,2}^{(2)} &= u^{-2\gamma_2}\beta_{0,2}c_{\gamma_2}b_X\int_0^\infty \varrho^{\gamma_2}ds = \frac{\beta_{0,2}c_{\gamma_2}b_X}{\gamma_2 b_V}\,(-B_\Delta)^{\gamma_2}\,.
\end{aligned}
$$

Case $\mathbf{a_V > 0}$. In this case,

$$
\psi_1(u,w,s) = -\frac{u(1+o(1/u))}{\sigma a_V(\sqrt{1-\rho^2}-\mathrm{i}\rho)}, \quad u\to+\infty, \tag{23}
$$

$$
\psi_1(0,-\mathrm{i}w,s) = \frac{we^{-b_V s}}{1+wAB_s} \tag{24}
$$

with $B_s = b_V^{-1}(\exp(-b_V s)-1)$. By (24), the function $l(w)$ remains bounded for all w such that $\mathrm{Re}\,w\geq 0$. Therefore, we have $l(\psi_1(u,0,\Delta)) = O(1)$ as $u\to+\infty$. The asymptotic relation (23) implies

$$
\begin{aligned}
\mathrm{Re}\{\psi_0(u,0,\Delta)\} &= -a_V\left[u\sigma^{-1}a_V^{-1}\sqrt{1-\rho^2}\Delta\right]+\\
&\quad+\mathrm{Re}\left\{\int_0^\Delta\left[\int_{-\infty}^\infty\int_0^\infty\left(e^{\mathrm{i}ux-[\sigma^{-1}a_V^{-1}(\sqrt{1-\rho^2}+\mathrm{i}\rho)u+o(1)]y}-1\right)\nu(dx,dy)\right]ds\right\}
\end{aligned}
$$

as $u\to+\infty$. Furthermore, Lemma 5.3 with $\varrho = u\sigma^{-1}a_V^{-1}\sqrt{1-\rho^2}$ and $\phi = u\sigma^{-1}a_V^{-1}\rho$ gives

$$
\begin{aligned}
\mathrm{Re}\{\psi_0(u,0,\Delta)\} &= -a_V\left[u\sigma^{-1}a_V^{-1}\sqrt{1-\rho^2}\,\Delta\right]+\\
&\quad+\int_0^\Delta\left[-\beta_{0,2}\,r_{\gamma_2}(a)\,\varrho^{\gamma_2}\left[1+\mathcal{R}_2(\varrho,\phi)\right]+\mathcal{R}(u)\right]ds+O(1), \quad u\to+\infty,
\end{aligned}
$$

where $a = \rho/\sqrt{1-\rho^2}$, $\mathcal{R}_2(\varrho,\phi) = (\bar{B}\beta_{1,2}/\beta_{0,2})\varrho^{-\chi_2}$, $\bar{B} = r_{\gamma_2-\chi_2}(a)/r_{\gamma_2}(a)$,

$$
\mathcal{R}(u) = -u^{\gamma_1}\left(\beta_{0,1}d_{\gamma_1}+\beta_{1,1}d_{\gamma_1-\chi_1}u^{-\chi_1}\right)
$$

and

$$
r_{\gamma_2}(a) = \int_0^\infty \frac{e^{-y}}{y^{\gamma_2}}(\cos(ay)+a\sin(ay))\,dy.
$$

Denote $\varsigma = \sigma a_V / \sqrt{1-\rho^2}$. Then the following relations hold

$$
\begin{aligned}
& a_V \left[u\sigma^{-1} a_V^{-1} \sqrt{1-\rho^2}\, \Delta \right] = a_V \varsigma^{-1} \Delta u, \\
& \int_0^{\Delta} \beta_{0,2}\, r_{\gamma_2}(\phi/\varrho)\, \varrho^{\gamma_2} ds = \beta_{0,2}\, r_{\gamma_2}(a) \, \left(\frac{u}{\varsigma}\right)^{\gamma_2} \Delta, \\
& \int_0^{\Delta} R(\varrho) \beta_{0,2}\, r_{\gamma_2}(\phi/\varrho)\, \varrho^{\gamma_2} ds = \beta_{0,2}\, r_{\gamma_2}(a)\, \bar{B} \frac{\beta_{1,2}}{\beta_{0,2}} \left(\frac{u}{\varsigma}\right)^{\gamma_2 - \chi_2} \Delta \\
& \int_0^{\Delta} \mathcal{R}_2(u) ds = -u^{\gamma_1} \Big(\beta_{0,1} d_{\gamma_1} + \beta_{1,1} d_{\gamma_1 - \chi_1} u^{-\chi_1} \Big) \Delta + O(1), \quad u \to +\infty.
\end{aligned}
$$

Combining the last formulas, we arrive at the representation

$$
\log |\phi(u)| = -\tau_1 u - \lambda_{1,1} u^{\gamma_1} - \lambda_{2,1} u^{\gamma_1 - \chi_1} - \lambda_{1,2} u^{\gamma_2} - \lambda_{2,2} u^{\gamma_2 - \chi_2} + O(1), \quad u \to +\infty, \tag{25}
$$

with

$$
\begin{aligned}
\tau_1 &= a_V \varsigma^{-1}, \\
\lambda_{1,1} &= \beta_{0,1} d_{\gamma_1}, \\
\lambda_{2,1} &= \beta_{1,1} d_{\gamma_1 - \chi_1}, \\
\lambda_{1,2} &= \beta_{0,2} r_{\gamma_2}(a) \varsigma^{-\gamma-2}, \\
\lambda_{2,2} &= \beta_{0,2}\, r_{\gamma_2}(a)\, \bar{B} \frac{\beta_{1,2}}{\beta_{0,2}}\, \varsigma^{\chi_2 - \gamma_2}.
\end{aligned}
$$

This completes the proof of Theorem 2.1.

4.2 Proof of Theorem 3.1

We begin the proof with the following lemma.

Lemma 4.2. *Suppose that*

$$
\widetilde{\varepsilon}_n := \left[\inf_{u \in [0, U_n]} |\phi(u)| \right]^{-2\theta} \frac{\log n}{\sqrt{n}} = o(1), \quad n \to \infty. \tag{26}
$$

Then there exist positive constants D_1, D_2, and δ such that for any $n > 1$

$$
\mathrm{P} \left\{ |\alpha_n - \bar{\alpha}_n| > D_1 \widetilde{\varepsilon}_n \int_0^{U_n} \left| w^{U_n}(u) \right| \left| \log^{-1} \left(\mathcal{G}(u) \right) \right| du \right\} \leq D_2 n^{-1-\delta}, \tag{27}
$$

where $\mathcal{G}(u) = |\phi(u)|^{2\theta} / |\phi(u\theta)|^2$.

Proof. We divide the proof into several steps.

1. Denote $\mathcal{G}_n(u) = |\phi_n(u)|^{2\theta} / |\phi_n(u\theta)|^2$. It holds

$$\begin{aligned} \mathcal{G}_n(u) - \mathcal{G}(u) &= \frac{|\phi_n(u)|^{2\theta} - |\phi(u)|^{2\theta}}{|\phi_n(u\theta)|^2} + \frac{|\phi(u)|^{2\theta}}{|\phi(u\theta)|^2} \frac{|\phi(u\theta)|^2 - |\phi_n(u\theta)|^2}{|\phi_n(u\theta)|^2} \\ &= \mathcal{G}(u) \left[\frac{\xi_{1,n}(u) + \xi_{2,n}(u)}{1 - \xi_{2,n}(u)} \right] = \mathcal{G}(u)\Lambda_n(u) \end{aligned} \tag{28}$$

with

$$\xi_{1,n}(u) = \frac{|\phi_n(u)|^{2\theta} - |\phi(u)|^{2\theta}}{|\phi(u)|^{2\theta}} \qquad \text{and} \qquad \xi_{2,n}(u) = \frac{|\phi(u\theta)|^2 - |\phi_n(u\theta)|^2}{|\phi(u\theta)|^2}.$$

2. Lemma 5.5 shows that the event

$$\mathcal{W}_n = \left\{ \sup_{u \in [0, U_n]} |\xi_{k,n}(u)| \le B_1 \, \widetilde{\varepsilon}_n, \; k = 1, 2 \right\}$$

has a probability that tends to 1 as n tends to infinity. More precisely, it holds

$$\mathrm{P}(\overline{\mathcal{W}}_n) = \mathrm{P}\left(\sup_{u \in [0, U_n]} |\xi_{k,n}(u)| > B_1 \widetilde{\varepsilon}_n \right) \le D_2 n^{-1-\delta}, \quad k = 1, 2 \tag{29}$$

for some positive constants B_1, D_2, and δ.

3. For any $u \in [\varepsilon U_n, U_n]$, the Taylor expansion for the function $f(x) = \log(-\log(x))$ in the vicinity of the point $x = \mathcal{G}(u)$ yields

$$\mathcal{Y}_n(u) - \mathcal{Y}(u) = \chi_1(u)(\mathcal{G}_n(u) - \mathcal{G}(u)) + \chi_2(u)(\mathcal{G}_n(u) - \mathcal{G}(u))^2 \tag{30}$$

with

$$\chi_1(u) = \mathcal{G}^{-1}(u) \log^{-1}(\mathcal{G}(u)) \qquad \text{and} \qquad |\chi_2(u)| \le 2^{-1} \max_{z \in I_n(u)} \left[\frac{1 + |\log(z)|}{z^2 \log^2(z)} \right], \tag{31}$$

where by $I_n(u)$ we denote the interval between $\mathcal{G}(u)$ and $\mathcal{G}_n(u)$. Due to (4),

$$\begin{aligned} \mathcal{G}(u) = \frac{|\phi(u)|^{2\theta}}{|\phi(\theta u)|^2} &= \exp\left\{2\tau_2 u^\alpha \left(-\theta \left(1 + r(u)\right) + \theta^\alpha \left(1 + r(\theta u)\right)\right)\right\} \\ &\le \exp\left\{A_1 u^\alpha + A_2 u^{\alpha - \varkappa}\right\}, \end{aligned}$$

where $A_1 = 2\tau_2 (\theta^\alpha - \theta) < 0$ and $A_2 = 2\tau_2\tau_3 (\theta^{\alpha-\varkappa} + \theta)$. Hence, $\mathcal{G}(u) \to 0$ as $u \to +\infty$. Moreover, the length of the interval $|I_n(u)| = \mathcal{G}(u)|\Lambda_n(u)|$ tends to 0 on the event $\mathcal{W}_n$, uniformly in $u \in [\varepsilon U_n, U_n]$. Thus, $I_n(u) \subset (0, 1)$ on $\mathcal{W}_n$ for n large enough and the maximum on the right hand side of the inequality in (31) is attained at one of the endpoints of the interval $I_n(u)$.

4. Denote $Q(u) = \chi_2(u)(\mathcal{G}_n(u) - \mathcal{G}(u))^2$. Lemma 5.6 shows that there exist a positive constant B_3 such that for any $u \in [\varepsilon U_n, U_n]$ and for n large enough

$$\mathcal{W}_n \subset \left\{ |Q(u)| \le B_3(\xi_{1,n}^2(u) + \xi_{2,n}^2(u)) \left|\log^{-1}\left(\mathcal{G}(u)\right)\right| \right\}. \tag{32}$$

5. The Taylor expansion (30) and previous discussion yield that on the set $\mathcal{W}_n$,

$$\begin{aligned}
|\alpha_n - \bar{\alpha}_n| &= \left|\int_0^{U_n} w^{U_n}(u)(\mathcal{Y}_n(u) - \mathcal{Y}(u))\,du\right| \\
&\le \int_0^{U_n} |w^{U_n}(u)| \left(\frac{|\mathcal{G}_n(u) - \mathcal{G}(u)|}{|\mathcal{G}(u)|}\left|\log^{-1}\left(\mathcal{G}(u)\right)\right| + |Q(u)|\right) du \\
&\le \int_0^{U_n} |w^{U_n}(u)| \log^{-1}\left(\mathcal{G}^{-1}(u)\right) \left(\frac{|\mathcal{G}_n(u) - \mathcal{G}(u)|}{|\mathcal{G}(u)|} + B_3(\xi_{1,n}^2(u) + \xi_{2,n}^2(u))\right) du.
\end{aligned}$$

By (28), expression in the brackets is equal to

$$P := \frac{|\mathcal{G}_n(u) - \mathcal{G}(u)|}{|\mathcal{G}(u)|} + B_3(\xi_{1,n}^2(u) + \xi_{2,n}^2(u)) \;\; = \;\; \frac{|\xi_{1,n}(u) + \xi_{2,n}(u)|}{|1 - \xi_{2,n}(u)|} + B_3(\xi_{1,n}^2(u) + \xi_{2,n}^2(u)),$$

and P can be upper bounded on the set $\mathcal{W}_n$ as follows (all supremums are taken over $[0, U_n]$):

$$\begin{aligned}
P &\le \frac{\sup|\xi_{1,n}(u)| + \sup|\xi_{2,n}(u)|}{1 - \sup|\xi_{2,n}(u)|} + B_3\left((\sup|\xi_{1,n}(u)|)^2 + (\sup|\xi_{2,n}(u)|)^2\right) \\
&\le \frac{2B_1\widetilde{\varepsilon}_n}{1 - B_1\widetilde{\varepsilon}_n} + 2B_3B_1^2\widetilde{\varepsilon}_n^2 \le D_1\widetilde{\varepsilon}_n.
\end{aligned}$$

This completes the proof. □

Now we proceed with the proof of Theorem (3.1). First, we get a lower bound for the infimum of the function $|\phi(u)|$ over $[0, U_n]$. Consider two cases (see Theorem 2.1):

1 $a_V > 0$ ($\tau_1 > 0$) In this case,

$$\begin{aligned}
\inf_{u\in[0,U_n]} |\phi(u)| = \inf_{u\in[1,U_n]} |\phi(u)| &= \inf_{u\in[1,U_n]} \exp\left\{-\tau_1 u - \tau_2 u^\alpha\left(1 + r(u)\right)\right\} \\
&\ge \inf_{u\in[1,U_n]} \exp\left\{-\tau_1 u - \tau_2 u^\alpha - \tau_2\tau_3 u^{\alpha-\varkappa}\right\} \\
&\ge \exp\left\{-\left(\tau_1 + \tau_2 + \tau_2\tau_3\right) U_n\right\}.
\end{aligned}$$

2 $a_V = 0$ ($\tau_1 = 0$) Following the same lines, we arrive at

$$\begin{aligned}
\inf_{u\in[0,U_n]} |\phi(u)| = \inf_{u\in[1,U_n]} |\phi(u)| &= \inf_{u\in[1,U_n]} \exp\left\{-\tau_2 u^\alpha - \tau_2\tau_3 u^{\alpha-\varkappa}\right\} \\
&\ge \exp\left\{-\left(\tau_2 + \tau_2\tau_3\right) U_n^\alpha\right\}.
\end{aligned}$$

Thus, we conclude that $\widetilde{\varepsilon}_n \leq \varepsilon_{1,n}$ in the first case and $\widetilde{\varepsilon}_n \leq \varepsilon_{2,n}$ in the second one, and therefore the assumption of Lemma 4.2 is fulfilled in both cases. Next,

$$\left|\log^{-1}\left(\mathcal{G}(u)\right)\right| = \frac{1}{2\tau_\theta u^\alpha R(u)}$$

with $\tau_\theta = \tau_2(\theta - \theta^\alpha)$ and

$$R(u) = 1 + \frac{\theta r(u) - \theta^\alpha r(\theta u)}{\theta - \theta^\alpha}.$$

Hence

$$\int_0^{U_n} \left|w^{U_n}(u)\right| \left|\log^{-1}\left(\mathcal{G}(u)\right)\right| du \quad = \quad \frac{1}{2\tau_\theta U_n^\alpha} \int_\varepsilon^1 \frac{|w^1(u)|}{u^\alpha R(U_n u)} du \leq \frac{C_2}{\tau_\theta U_n^\alpha}$$

for some $C_2 > 0$ and the statement of the theorem follows.

5 Auxiliary results

Lemma 5.1. *Consider a Lévy measure ν on $\mathbb{R}_+$ that satisfies*

$$\Pi(\varepsilon) := \int_\varepsilon^\infty \nu(dy) = \varepsilon^{-\gamma}(\beta_0 + \beta_1 \varepsilon^\chi (1 + O(\varepsilon))), \quad \varepsilon \to +0, \tag{33}$$

with $0 < \chi < \gamma < 1$ and $\beta_0 > 0$. Denote

$$\Phi(\rho, \phi) = \int_0^\infty \left(e^{-\varrho z}\cos(\phi z) - 1\right) \nu(dz),$$

then the following asymptotic relations hold.

(i) *As $\phi, \varrho \to \infty$,*

$$\Phi(\varrho,\phi) = \begin{cases} -\varrho^\gamma \left[\beta_0 c_\gamma \left(1 + \phi/\varrho\right) + \beta_1 c_{\gamma-\chi} \varrho^{-\chi}\right] + O\left(e^{-\phi}\right), & \varrho/\phi \to +\infty, \\ -\phi^\gamma \Big[\beta_0 d_\gamma + \beta_0 e_\gamma \left(\varrho/\phi\right) + \beta_1 (d_{\gamma-\chi} + e_{\gamma-\chi}) \phi^{-\chi} \left(\varrho/\phi\right)\Big] + O\left(e^{-\varrho}\right), & \phi/\varrho \to +\infty, \end{cases}$$

where $c_\gamma = \Gamma(1-\gamma)$, $d_\gamma = \Gamma(1-\gamma)\sin((1-\gamma)\pi/2)$, and $e_\gamma = \Gamma(1-\gamma)\cos((1-\gamma)\pi/2)$.

(ii) *As $\phi, \varrho \to \infty$ and $\phi/\varrho = a$ for some constant $a > 0$,*

$$\Phi(\varrho,\phi) = -\varrho^\gamma \left[\beta_0 r_\gamma(a) + \beta_1 r_{\gamma-\chi}(a) \varrho^{-\chi}\right] + O\left(e^{-\varrho}\right)$$

with

$$r_\gamma(a) = \int_0^\infty \frac{e^{-y}}{y^\gamma}(\cos(ay) + a\sin(ay))\, dy.$$

Proof. **(i)** Here we present the proof only for the case $\phi/\varrho \to +\infty$. The case $\varrho/\phi \to +\infty$ can be treated in a similar way.

i1. Integrating by parts, we get

$$\begin{aligned}\int_0^{\infty}\left(e^{-\varrho z}\cos(\phi z)-1\right)\nu(dz) &= \int_0^{\infty}\left(e^{-y}\cos(\phi y/\rho)-1\right)\nu(d(y/\varrho)) \\ &= -\left(e^{-y}\cos(\phi y/\rho)-1\right)\Pi(y/\varrho)\big|_0^{\infty} \\ &\quad -\int_0^{\infty}\Pi(y/\varrho)e^{-y}\Big(\cos(\phi y/\varrho)+\phi/\varrho\ \sin(\phi y/\varrho)\Big)dy.\end{aligned}$$

Hence

$$\begin{aligned}\int_0^{\infty}\left(e^{-\varrho z}\cos(\phi z)-1\right)\nu(dz) &= -\varrho^{\gamma}\int_0^{\infty}(y/\varrho)^{\gamma}\Pi(y/\varrho)\frac{e^{-y}}{y^{\gamma}}\cos(\phi y/\varrho)dy \\ &\quad -\phi\varrho^{\gamma-1}\int_0^{\infty}(y/\varrho)^{\gamma}\Pi(y/\varrho)\frac{e^{-y}}{y^{\gamma}}\sin(\phi y/\varrho)dy \\ &= -\varrho^{\gamma}I_1-\phi\varrho^{\gamma-1}I_2.\end{aligned}$$

i2. Take $H=\varrho^p$ with $0<p<1$, and represent I_1 as a sum of two integrals:

$$\begin{aligned}I_1=\int_0^{\infty}(y/\varrho)^{\gamma}\Pi(y/\varrho)\frac{e^{-y}}{y^{\gamma}}\cos(\phi y/\varrho)dy &= \int_0^{H}(y/\varrho)^{\gamma}\Pi(y/\varrho)\frac{e^{-y}}{y^{\gamma}}\cos(\phi y/\varrho)dy \\ &\quad +\int_H^{\infty}\rho^{-\gamma}\Pi(y/\varrho)e^{-y}\cos(\phi y/\varrho)dy.\end{aligned}$$

The function $\varrho^{-\gamma}\Pi(y/\varrho)$ is uniformly bounded for $y>H$ as $\varrho\to+\infty$. Indeed,

$$\begin{aligned}\varrho^{-\gamma}\ \Pi(y/\varrho) &\le \varrho^{-\gamma}\ \Pi(H/\varrho) \\ &= \varrho^{-p\gamma}\Big(\beta_0+\beta_1\varrho^{\chi(p-1)}\left(1+O(\varrho^{p-1})\right)\Big) \\ &= \beta_0\varrho^{-p\gamma}+\beta_1\varrho^{-\left(\chi+(\gamma-\chi)p\right)}\left(1+\varrho^{p-1}O(1)\right)\end{aligned}$$

and $\chi+(\gamma-\chi)p>0$. This boundeness of $\rho^{-\gamma}\Pi(y/\varrho)$ implies

$$\int_H^{+\infty}\rho^{-\gamma}\Pi(y/\varrho)e^{-y}\cos(\phi y/\varrho)dy=O(e^{-H}).$$

As a result,

$$I_1=\int_0^{H}(y/\varrho)^{\gamma}\Pi(y/\varrho)\frac{e^{-y}}{y^{\gamma}}\cos(\phi y/\varrho)dy+O(e^{-H}).$$

i3. If $\rho\to\infty$ and $y<H$, the assumption (33) implies

$$\begin{aligned}I_1 &= \beta_0\int_0^{H}\frac{e^{-y}}{y^{\gamma}}\cos(\phi y/\varrho)dy+\beta_1\varrho^{-\chi}\int_0^{H}\frac{e^{-y}}{y^{\gamma-\chi}}\cos(\phi y/\varrho)dy \\ &\quad +O\left(\varrho^{-\chi-1}\int_0^{H}\frac{e^{-y}}{y^{\gamma-\chi-1}}dy\right)+O(e^{-H}).\end{aligned}$$

Note now that

$$\begin{aligned}
\int_0^H \frac{e^{-y}}{y^\gamma}\cos(\phi y/\varrho)dy &= \int_0^\infty \frac{e^{-y}}{y^\gamma}\cos(\phi y/\varrho)dy - \int_H^\infty \frac{e^{-y}}{y^\gamma}\cos(\phi y/\varrho)dy \\
&= \int_0^\infty \frac{e^{-y}}{y^\gamma}\cos(\phi y/\varrho)dy + O(e^{-H}H^{-\gamma}).
\end{aligned}$$

Analogously,

$$\int_0^H \frac{e^{-y}}{y^{\gamma-\chi}}\cos(\phi y/\varrho)dy = \int_0^\infty \frac{e^{-y}}{y^{\gamma-\chi}}\cos(\phi y/\varrho)dy + O(e^{-H}H^{\chi-\gamma}),$$

and we conclude that

$$I_1 = \beta_0 \int_0^\infty \frac{e^{-y}}{y^\gamma}\cos(\phi y/\varrho)dy + \beta_1\varrho^{-\chi}\int_0^\infty \frac{e^{-y}}{y^{\gamma-\chi}}\cos(\phi y/\varrho)dy + T_1,$$

where

$$\begin{aligned}
T_1 &= O\left(\varrho^{-\chi-1}\int_0^H \frac{e^{-y}}{y^{\gamma-\chi-1}}dy\right) + O(e^{-H}H^{-\gamma}) + O\left(\varrho^{-\chi}e^{-H}H^{\gamma-\chi}\right) + O(e^{-H}) \\
&= O\left(\varrho^{-\gamma}e^{-H}\right).
\end{aligned}$$

i4. Since

$$\int_0^\infty \frac{e^{-y}}{y^\gamma}\cos(hy)dy \asymp e_\gamma h^{\gamma-1}, \quad h \to +\infty$$

with $e_\gamma = \Gamma(1-\gamma)\cos((1-\gamma)\pi/2)$, we get

$$\varrho^\gamma I_1 = \phi^\gamma\Big[\beta_0 e_\gamma(\varrho/\phi) + \beta_1 e_{\gamma-\chi}\phi^{-\chi}(\varrho/\phi)\Big] + O(e^{-H}), \quad \varrho,\phi \to \infty.$$

Similarly, using the fact that

$$\int_0^\infty \frac{e^{-y}}{y^\gamma}\sin(hy)dy \asymp d_\gamma h^{\gamma-1}, \quad h \to \infty$$

with $e_\gamma = \Gamma(1-\gamma)\sin((1-\gamma)\pi/2)$, we arrive at

$$\phi\varrho^{\gamma-1}I_2 = \phi^\gamma\left[\beta_0 d_\gamma + \beta_1 d_{\gamma-\chi}\phi^{-\chi}\right] + O(e^{-H}), \quad \varrho,\phi \to \infty.$$

(ii) The first three steps are the same as i1, i2 and i3.

ii4. Introduce

$$v_\gamma(a) = \int_0^\infty \frac{e^{-y}\cos(ay)}{y^\gamma} dy,$$

then

$$\varrho^\gamma I_1 = \varrho^\gamma \Big[\beta_0 v_\gamma(a) + \beta_1 v_{\gamma-\chi}(a)\varrho^{-\chi}\Big] + O\left(e^{-H}\right).$$

Analogously,

$$\phi\varrho^{\gamma-1} I_2 = a\varrho^\gamma I_2 = a\varrho^\gamma \Big[\beta_0 w_\gamma(a) + \beta_1 w_{\gamma-\chi}(a)\varrho^{-\chi}\Big] + O\left(e^{-H}\right)$$

with

$$w_\gamma(a) = \int_0^\infty \frac{e^{-y}\sin(ay)}{y^\gamma}\, dy.$$

It remains to note that

$$r_\gamma(a) = v_\gamma(a) + a w_\gamma(a).$$

□

Lemma 5.2. *Consider a Lévy measure ν on $\mathbb{R}\setminus\{0\}$ that fulfilles*

$$G(\varepsilon) := \int_{|x|>\varepsilon} \nu(dx) = \varepsilon^{-\gamma}(\beta_0 + \beta_1\varepsilon^\chi(1+O(\varepsilon))), \quad \varepsilon \to +0 \tag{34}$$

with $0<\chi<\gamma<1$ and $\beta_0>0$. Denote

$$V(u) \;=\; \int_{\mathbb{R}} \big(\cos(ux)-1\big) d\nu(x).$$

Then as $u\to+\infty$,

$$V(u) \;=\; -u^\gamma\Big(\beta_0 d_\gamma + \beta_1 d_{\gamma-\chi} u^{-\chi}\Big) + O(1).$$

Proof. For the sake of simplicity we consider only the case of even measure ν.

1. First, we apply the integration by parts to get

$$\begin{aligned} V(u) &= -\int_0^{+\infty} \big(\cos(ux)-1\big) dG(x) \\ &= -\big(\cos(ux)-1\big)G(x)\big|_0^{+\infty} - u\int_0^{+\infty} \sin(ux)G(x)dx \\ &= -\int_0^{+\infty} \sin(x)G(x/u)dx. \end{aligned}$$

2. Take $H = u^p$ with $0 < p < 1$, and represent the last integral as a sum of tho integrals:

$$\begin{aligned}\int_0^{+\infty} \sin(x) G(x/u) dx &= \int_0^H \sin(x) G(x/u) dx + \int_H^{+\infty} \sin(x) G(x/u) dx \\ &= I_1 + I_2.\end{aligned}$$

The integral I_2 is bounded, because $G(x/u)$ is uniformly bounded for $x > H$ by $G(H/u)$.

3. Next, we apply (34) to I_1:

$$\begin{aligned}I_1 &= \int_0^H \sin(x) \, (x/u)^{-\gamma} \left(\beta_0 + \beta_1 \, (x/u)^{\chi} \, (1 + O\,(x/u))\right) \\ &= \beta_0 u^{\gamma} \int_0^H \frac{\sin(x)}{x^{\gamma}} dx + \beta_1 u^{\gamma-\chi} \int_0^H \frac{\sin(x)}{x^{\gamma-\chi}} dx + \beta_1 u^{\gamma-\chi-1} \int_0^H \frac{\sin(x)}{x^{\gamma-\chi-1}} dx.\end{aligned}$$

Note that the integral $\int_0^H \sin(x) x^{-\gamma} dx$ can be represented in the following way:

$$\int_0^H \frac{\sin(x)}{x^{\gamma}} dx = \int_0^{\infty} \frac{\sin(x)}{x^{\gamma}} dx - \int_H^{\infty} \frac{\sin(x)}{x^{\gamma}} dx = d_{\gamma} + O(H^{-\gamma}).$$

Analogously,

$$\int_0^H \frac{\sin(x)}{x^{\gamma-\chi}} dx = d_{\gamma-\chi} + O(H^{-(\gamma-\chi)}).$$

Finally, we arrive at

$$I_1 = \beta_0 d_{\gamma} u^{\gamma} + \beta_1 d_{\gamma-\chi} u^{\gamma-\chi} + T_1,$$

where

$$T_1 = O(u^{(1-p)\gamma}) + O(u^{(1-p)(\gamma-\chi)}) + O(u^{(1-p)(\gamma-\chi-1)}) = O(u^{(1-p)\gamma}).$$

$\square$

Lemma 5.3. *Let ν be a two-dimensional Lévy measure on $\mathbb{R} \times \mathbb{R}_+$ with marginals ν_1 and ν_2, and assumptions (AN1) and (AN2) are fulfilled. Denote*

$$Q(u, \varrho, \phi) = \int_{-\infty}^{\infty} \int_0^{\infty} \left(\exp\Big\{ \mathrm{i}ux - (\varrho + \mathrm{i}\phi) y \Big\} - 1 \right) \nu(dx, dy)$$

for any real numbers u, ϱ and ϕ. Then

$$\mathrm{Re}\{Q(u, \varrho, \phi)\} = \Phi(\rho, \phi) + \mathcal{R}(u) + O(1), \qquad u, \varrho, \phi \to +\infty$$

with

$$\Phi(\rho,\phi)=\int_0^\infty\left(e^{-\varrho y}\cos(\phi y)-1\right)\nu_2(dy)$$

and

$$\mathcal{R}(u) \;=\; -u^{\gamma_1}\Big(\beta_{0,1}d_{\gamma_1}+\beta_{1,1}d_{\gamma_1-\chi_1}u^{-\chi_1}\Big).$$

Moreover, the following asymptotic relations hold as $\varrho,\phi\to+\infty$

$$\begin{aligned}\mathrm{Re}\{Q(u,\varrho,\phi)\} &= -\beta_{0,2}c_{\gamma_2}\varrho^{\gamma_2}\left[1+\mathcal{R}_1(\varrho,\phi)\right]+\mathcal{R}(u)+O(1), \quad \varrho/\phi\to+\infty,\\ \mathrm{Re}\{Q(u,\varrho,\phi)\} &= -\beta_{0,2}r_{\gamma_2}(a)\varrho^{\gamma_2}\left[1+\mathcal{R}_2(\varrho,\phi)\right]+\mathcal{R}(u)+O(1), \quad \phi/\varrho=a,\end{aligned}$$

where

$$\mathcal{R}_1(\varrho,\phi)=\bar{A}\frac{\beta_{1,2}}{\beta_{0,2}}\varrho^{-\chi_2}+\frac{\phi}{\varrho}, \quad \mathcal{R}_2(\varrho,\phi)=(\bar{B}\beta_{1,2}/\beta_{0,2})\varrho^{-\chi_2}$$

and $\bar{A}$, $\bar{B}$ *are two absolute constants.*

Proof. We have

$$\begin{aligned}\mathrm{Re}\left[Q(u,\varrho,\phi)\right] &= \int_0^\infty\left(\exp(-\varrho y)\cos(\phi y)-1\right)\nu_2(dy)\\ &\quad+\int_{-\infty}^\infty\int_0^\infty\left(\cos(ux)-1\right)\cdot\exp(-\varrho y)\cos(\phi y)\nu(dx,dy)\\ &\quad+\int_{-\infty}^\infty\int_0^\infty\sin(ux)\sin(\phi y)\exp(-\varrho y)\nu(dx,dy)=\Phi(\varrho,\phi)+I_1(u,\varrho,\phi)+I_2(u,\varrho,\phi).\end{aligned}$$

Consider for simplicity the case of the Lévy measure ν with independent components. In this case (see Cont, Tankov, 2004),

$$I_1(u,\varrho,\phi)=\int_{-\infty}^\infty\left(1-\cos(ux)\right)\nu_1(dx), \qquad I_2(u,\varrho,\phi)=\int_{-\infty}^\infty\sin(ux)\nu_1(dx).$$

The asymptotical behavior of these integrals is given by Lemma 5.2. Other statements directly follow from Lemma 5.1. The constants $\bar{A}$ and $\bar{B}$ are equal to

$$\bar{A}=c_{\gamma_2-\chi_2}/c_{\gamma_2}, \qquad \bar{B}=r_{\gamma_2-\chi_2}(a)/r_{\gamma_2}(a).$$

This completes the proof. ☐

Lemma 5.4. *For any* n *large enough, it holds*

$$|\alpha-\bar{\alpha}_n|\le c\tau_3U_n^{-\varkappa} \tag{35}$$

with some constant c *not depending on* n.

Proof. Denote

$$R(u) = 1 + \frac{\theta r(u) - \theta^\alpha r(\theta u)}{\theta - \theta^\alpha},$$

then

$$\begin{aligned}
|\alpha - \bar{\alpha}_n| &= \left|\alpha - \int_0^{U_n} w^{U_n}(u)\mathcal{Y}(u)du\right| = \left|\alpha - \int_0^{U_n} w^{U_n}(u)\log(2\tau_\theta u^\alpha R(u))du\right| = \\
&= \left|\alpha - \log(2\tau_\theta)\int_0^{U_n} w^{U_n}(u)du - \alpha\int_0^{U_n} w^{U_n}(u)\log u\, du - \int_0^{U_n} w^{U_n}(u)\log R(u)du\right| \\
&= \left|\int_0^{U_n} w^{U_n}(u)\log\Big(1 + \frac{\theta r(u) - \theta^\alpha r(\theta u)}{\theta - \theta^\alpha}\Big)du\right| \\
&= \left|\int_0^1 w^1(s)\log\Big(1 + \frac{\theta r(sU_n) - \theta^\alpha r(\theta sU_n)}{\theta - \theta^\alpha}\Big)ds\right|.
\end{aligned}$$

Since the function w^1 is supported on $[\varepsilon, 1]$, the lower bound of the integral can be changed to ε. It follows from

$$|r(u)| \le \tau_3 u^{-\varkappa}, \quad u > 1$$

that

$$\left|\frac{\theta r(sU_n) - \theta^\alpha r(\theta sU_n)}{\theta - \theta^\alpha}\right| \le \frac{\theta\tau_3(sU_n)^{-\varkappa} + \theta^\alpha\tau_3(\theta sU_n)^{-\varkappa}}{\theta - \theta^\alpha} = \tau_3 U_n^{-\varkappa}s^{-\varkappa}\,\frac{\theta + \theta^{\alpha-\varkappa}}{\theta - \theta^\alpha}$$

for n large enough (more precisely, for n s.t. $\varepsilon U_n > 1$). Hence for n large enough

$$\left|\frac{\theta r(sU_n) - \theta^\alpha r(\theta sU_n)}{\theta - \theta^\alpha}\right| \le \frac{1}{2}$$

and

$$|\alpha - \bar{\alpha}_n| \le \tau_3 U_n^{-\varkappa}\frac{\theta + \theta^{\alpha-\varkappa}}{\theta - \theta^\alpha}\int_\varepsilon^1 |w^1(s)|s^{-\varkappa}ds, \tag{36}$$

as $|\log(1+x)| \le 2|x|$ for any $|x| \le 1/2$. The observation that the integral on the right hand side of (36) is finite completes the proof. ☐

Lemma 5.5. *Let the assumptions (AM) and (AE) be fulfilled. Denote*

$$\xi_{1,n}(u) = \frac{|\phi_n(u)|^{2\theta} - |\phi(u)|^{2\theta}}{|\phi(u)|^{2\theta}}, \qquad \xi_{2,n}(u) = \frac{|\phi(u\theta)|^2 - |\phi_n(u\theta)|^2}{|\phi(u\theta)|^2}, \tag{37}$$

and

$$\widetilde{\varepsilon}_n = \left[\inf_{u\in[0,U_n]}|\phi(u)|\right]^{-2\theta}\frac{\log n}{\sqrt{n}}. \tag{38}$$

There exist some positive constants B_1, B_2, and δ such that

$$\mathrm{P}\left\{\sup_{u\in[0,U_n]}|\xi_{k,n}(u)| > B_1\widetilde{\varepsilon}_n\right\} \le B_2 n^{-1-\delta}, \quad k = 1, 2. \tag{39}$$

Proof. Denote

$$
\begin{aligned}
H_1 &= \left[\inf_{u\in[0,U_n]} |\phi(u)|\right]^{2\theta} \sup_{u\in[0,U_n]} \frac{\left||\phi_n(u)|^{2\theta} - |\phi(u)|^{2\theta}\right|}{|\phi(u)|^{2\theta}}, \\
H_2 &= \left[\inf_{u\in[0,U_n]} |\phi(u)|\right]^{2\theta} \sup_{u\in[0,U_n]} \frac{\left||\phi_n(u\theta)|^{2} - |\phi(u\theta)|^{2}\right|}{|\phi(u\theta)|^{2}}.
\end{aligned}
$$

Substituting (37) and (38) into (39), we obtain an equivalent formulation of the statement of the lemma:

$$
\begin{cases}
\mathrm{P}\left\{\frac{\sqrt{n}}{\log n} H_1 > B_1\right\} &\leq B_2 n^{-1-\delta}, \\
\mathrm{P}\left\{\frac{\sqrt{n}}{\log n} H_2 > B_1\right\} &\leq B_2 n^{-1-\delta}.
\end{cases}
\tag{40}
$$

Denote $w^*(u) = \log^{-1/2}(e + |u|)$. The quantity H_1 can be upper bounded as follows:

$$
\begin{aligned}
H_1 &\leq \left[\inf_{u\in[0,U_n]} |\phi(u)|\right]^{2\theta} \frac{\sup_{u\in[0,U_n]} \left||\phi_n(u)|^{2\theta} - |\phi(u)|^{2\theta}\right|}{\inf_{u\in[0,U_n]} |\phi(u)|^{2\theta}} \\
&\leq 2\theta \sup_{u\in[0,U_n]} |\phi_n(u) - \phi(u)| \\
&\leq 2\theta \sup_{u\in[0,U_n]} \left[\frac{w^*(u)}{\inf_{s\in[0,U_n]} w^*(s)} |\phi_n(u) - \phi(u)|\right] \\
&\leq 2\theta \sqrt{\log(e + U_n)} \sup_{u\in[0,U_n]} \left[w^*(u) |\phi_n(u) - \phi(u)|\right] \\
&\leq C_1 \sqrt{\log n} \sup_{u\in[0,U_n]} \left[w^*(u) |\phi_n(u) - \phi(u)|\right] \\
&\leq C_1 \sqrt{\log n} \sup_{u\in\mathbb{R}} \left[w^*(u) |\phi_n(u) - \phi(u)|\right],
\end{aligned}
$$

for some constant C_1. The quantity H_2 can be upper bounded in a similar way:

$$
\begin{aligned}
H_2 &\leq \left[\inf_{u\in[0,U_n]} |\phi(u)|\right]^{2\theta} \frac{\sup_{u\in[0,U_n\theta]} \left||\phi_n(u)|^{2} - |\phi(u)|^{2}\right|}{\inf_{u\in[0,U_n\theta]} |\phi(u)|^{2}} \\
&\leq \left[\inf_{u\in[0,U_n\theta]} |\phi(u)|\right]^{2\theta-2} \sup_{u\in[0,U_n\theta]} \left||\phi_n(u)|^{2} - |\phi(u)|^{2}\right| \\
&\leq 2 \sup_{u\in[0,U_n\theta]} |\phi_n(u) - \phi(u)| \\
&\leq C_2 \sqrt{\log n} \sup_{u\in\mathbb{R}} \left[w^*(u) |\phi_n(u) - \phi(u)|\right].
\end{aligned}
$$

Note that under the assumptions (AE) and (AM) the sequence $X_{k\Delta} - X_{(k-1)\Delta}$, $k = 2, \ldots, n$, is strongly mixing and ergodic with exponentially decreasing mixing coefficients (see Masuda, 2007). By the Proposition 6.3, there exist positive constants $B_1^{(0)}$, B_2 and δ such that

$$
\mathrm{P}\left\{\sqrt{\frac{n}{\log n}} \sup_{u\in\mathbb{R}} \Big[w^*(u) |\phi_n(u) - \phi(u)|\Big] > C_1 B_1^{(0)}\right\} \leq B_2 n^{-1-\delta}.
$$

Combining this result with the upper bounds for H_1 and H_2, we arrive at

$$\mathrm{P}\left\{\frac{\sqrt{n}}{\log n}\, H_1 > C_1 B_1^{(0)}\right\} \;\leq\; \mathrm{P}\left\{\sqrt{\frac{n}{\log n}}\, \sup_{u\in\mathbb{R}} \left[w^*(u)\, |\phi_n(u)-\phi(u)|\right] > B_1^{(0)}\right\} \leq B_2 n^{-1-\delta}$$

and

$$\mathrm{P}\left\{\frac{\sqrt{n}}{\log n}\, H_2 > C_2 B_1^{(0)}\right\} \;\leq\; \mathrm{P}\left\{\sqrt{\frac{n}{\log n}}\, \sup_{u\in\mathbb{R}} \left[w^*(u)\, |\phi_n(u)-\phi(u)|\right] > B_1^{(0)}\right\} \leq B_2 n^{-1-\delta}.$$

Formulae (40) follow with $B_1 = B_1^{(0)} \cdot \max\{C_1, C_2\}$. $\square$

Lemma 5.6. *Denote $Q(u) = \chi_2(u)(\mathcal{G}_n(u) - \mathcal{G}(u))^2$ and let $\widetilde{\varepsilon}_n = o(1)$. Then*

$$\mathcal{W}_n := \left\{\sup_{v\in[0,U_n]} |\xi_{k,n}(v)| \leq B_1\, \widetilde{\varepsilon}_n,\ k=1,2\right\} \subset \left\{|Q(u)| \leq B_3(\xi_{1,n}^2(u) + \xi_{2,n}^2(u))\left|\log^{-1}(\mathcal{G}(u))\right|\right\}$$

for some positive constant B_3, n large enough, and all $u \in [\varepsilon U_n, U_n]$.

Proof. Denote

$$S(u) = |Q(u)|\, \frac{|\log(\mathcal{G}(u))|}{\xi_{1,n}^2(u) + \xi_{2,n}^2(u)}.$$

By formula (28) and a trivial inequality $(a+b)^2 \leq 2\,(a^2+b^2)$, we get

$$(\mathcal{G}_n(u) - \mathcal{G}(u))^2 = \mathcal{G}^2(u)\Lambda_n^2(u) \leq 2\,\mathcal{G}^2(u)\frac{\xi_{1,n}^2(u) + \xi_{2,n}^2(u)}{(1-\xi_{2,n}(u))^2}.$$

Hence

$$S(u) \leq 2\,|\chi_2(u)|\, \frac{\mathcal{G}^2(u)\,|\log(\mathcal{G}(u))|}{(1-\xi_{2,n}(u))^2}.$$

Let us now show that for n large enough

$$\mathcal{W}_n \subset \left\{\omega : |\Lambda_n(u)| \leq \frac{1}{2}\right\}.$$

In fact, we have on $\mathcal{W}_n$ for n large enough:

$$\begin{aligned} |\Lambda_n(u)| &= \frac{|\xi_{1,n}(u) + \xi_{2,n}(u)|}{|1-\xi_{2,n}(u)|} \leq \frac{\sup|\xi_{1,n}(u)| + \sup|\xi_{2,n}(u)|}{1-\sup|\xi_{2,n}(u)|} \\ &\leq \frac{2B_1\tilde{\varepsilon}_n}{1-B_1\tilde{\varepsilon}_n} \leq \frac{1}{2} \end{aligned}$$

because $\tilde{\varepsilon}_n = o(1)$. By (31), we get

$$|\chi_2(u)| \leq 2^{-1} \max_{z\in I_1(u)} \left[\frac{1+|\log(z\mathcal{G}(u))|}{z^2\mathcal{G}^2(u)\log^2(z\mathcal{G}(u))}\right],$$

where $I_1(u)$ is an interval between 1 and $1+\Lambda_n(u)$. On the set $\mathcal{W}_n$, we have $I_1(u) \subset [1/2, 3/2]$. Therefore

$$\begin{aligned} |\chi_2(u)|\, \mathcal{G}^2(u)\, |\log(\mathcal{G}(u))| &\leq 2^{-1} \max_{z\in[1/2,3/2]} \left[\frac{1+|\log(z\mathcal{G}(u))|}{\log^2(z\mathcal{G}(u))}\right] |\log(\mathcal{G}(u))| \\ &\leq 2^{-1} \frac{\left(1+\left|\log(\frac{1}{2}\mathcal{G}(u))\right|\right) |\log(\mathcal{G}(u))|}{\left|\log(\frac{1}{2}\mathcal{G}(u))\right|^2}. \end{aligned}$$

Since $\sup_{u\in[\varepsilon U_n, U_n]} |\mathcal{G}(u)| \to 0$ as $n\to\infty$, the function $|\chi_2(u)|\, \mathcal{G}^2(u)\, |\log(\mathcal{G}(u))|$ is bounded on $[\varepsilon U_n, U_n]$ by a constant $\widetilde{C}$. So, we have proved that on $\mathcal{W}_n$,

$$S(u) \leq \frac{2\,\widetilde{C}}{(1-\xi_{2,n}(u))^2},$$

for u large enough. Moreover, it holds on $\mathcal{W}_n$

$$\begin{aligned} S(u) &\leq \frac{C}{(1-\xi_{2,n}(u))^2} \leq \sup_{u\in[0,U_n]} \frac{C}{(1-\xi_{2,n}(u))^2} \leq \frac{C}{\left(1-\sup_{u\in[0,U_n]}|\xi_{2,n}(u)|\right)^2} \\ &\leq \frac{C}{(1-B_1\widetilde{\varepsilon}_n)^2} \leq B_3 \end{aligned}$$

for some B_3, $C = 2\widetilde{C}$ and n large enough. This completes the proof.

□

6 Appendix. Exponential inequalities for dependent sequences and for empirical characteristic functions

The following theorem can be found in Merlevéde, Peligrad, and Rio, 2009.

Theorem 6.1. *Let $(Z_k,\ k\geq 1)$ be a strongly mixing sequence of centered real-valued random variables on the probability space $(\Omega, \mathcal{F}, \mathcal{P})$ with the mixing coefficients satisfying*

$$\alpha(n) \leq \bar{\alpha}\exp(-cn), \quad n\geq 1, \quad \bar{\alpha}>0, \quad c>0. \tag{41}$$

Assume that $\sup_{k\geq 1}|Z_k| \leq M$ a.s., then there is a positive constant C depending on c and $\bar{\alpha}$ such that

$$\mathrm{P}\left\{\sum_{i=1}^n Z_i \geq \zeta\right\} \leq \exp\left[-\frac{C\zeta^2}{nv^2+M^2+M\zeta\log^2(n)}\right].$$

for all $\zeta>0$ and $n\geq 4$, where

$$v^2 = \sup_i \left(\mathbb{E}[Z_i]^2 + 2\sum_{j\geq i}\operatorname{Cov}(Z_i,Z_j)\right).$$

Corollary 6.2. *Denote*

$$\rho_j = \mathbb{E}\left[Z_j^2 \log^{2(1+\varepsilon)}\left(|Z_j|^2\right)\right], \quad j = 1, 2, \ldots,$$

with arbitrary small $\varepsilon > 0$ and suppose that all ρ_j are finite. Then

$$\sum_{j \geq i} \mathrm{Cov}(Z_i, Z_j) \leq C \max_j \rho_j$$

for some constant $C > 0$, provided (41) *holds. Consequently the following inequality holds*

$$v^2 \leq \sup_i \mathbb{E}[Z_i]^2 + C \max_j \rho_j.$$

Proof. Due to the Rio inequality

$$|\mathrm{Cov}(Z_i, Z_j)| \leq 2 \int_0^{\alpha(|j-i|)} Q_{Z_i}(u) Q_{Z_j}(u) du$$

where for any random variable X we denote by Q_X the quantile function of X. Define

$$\rho_X = \mathbb{E}\left[X^2 \log^{2(1+\varepsilon)}\left(|X|^2\right)\right].$$

The Markov inequality implies for small enough $u > 0$

$$\begin{aligned}
\mathrm{P}\left(|X| > \frac{\rho_X^{1/2}}{u^{1/2}|\log(u)|^{(1+\varepsilon)}}\right) &\leq \mathbb{E}\left[X^2 \log^{2(1+\varepsilon)}\left(|X|^2\right))\right] \frac{\rho_X^{-1}}{u^{-1}\log^{-2(1+\varepsilon)}(u)} \\
&\quad \times \log^{-2(1+\varepsilon)}\left(\frac{\rho_X}{u \log^{2(1+\varepsilon)}(u)}\right) \\
&= u \log^{-2(1+\varepsilon)}\left(\rho_X \log^{-2(1+\varepsilon)}(u)\right) \leq u
\end{aligned}$$

and therefore

$$Q_X(u) \leq \frac{\rho_X^{1/2}}{u^{1/2}|\log(u)|^{(1+\varepsilon)}}.$$

Hence

$$|\mathrm{Cov}(Z_i, Z_j)| \leq 2 \int_0^{\alpha(|j-i|)} \frac{\sqrt{\rho_i \rho_j}}{u \log^{2(1+\varepsilon)}(u)} du \leq 2\sqrt{\rho_i \rho_j} \log^{-1-2\varepsilon}(\alpha(|j-i|))$$

and

$$\sum_{j \geq i} \mathrm{Cov}(Z_i, Z_j) \leq C \sqrt{\rho_i \rho_j} \sum_{j > i} \frac{1}{|j-i|^{1+2\varepsilon}}$$

with some constant $C > 0$ depending on $\bar{\alpha}$. $\square$

Let $Z_j,\, j=1,\ldots,n,$ be a sequence of random variables. Define

$$\phi_n(u) \;=\; \frac{1}{n}\sum_{j=1}^{n}\exp(\mathrm{i}uZ_j).$$

Proposition 6.3. *Suppose that the following assumptions hold:*

(AZ1) *The sequence $Z_j,\, j=1,\ldots,n,$ is strictly stationary and is α-mixing with mixing coefficients $(\alpha_Z(k))_{k\in\mathbb{N}}$ satisfying*

$$\alpha_Z(k) \le \bar{\alpha}_0 \exp(-\bar{\alpha}_1 k), \quad k\in\mathbb{N}$$

for some $\bar{\alpha}_0>0$ and $\bar{\alpha}_1>0.$

(AZ2) *The r.v. Z_j possess finite absolute moments of order $p>2.$*

Let w be a positive monotone decreasing Lipschitz function on $\mathbb{R}_+$ such that

$$0<w(z)\le \log^{-1/2}(e+|z|), \quad z\in\mathbb{R}. \tag{42}$$

Then there is $\delta'>0$ and $\xi_0>0$, such that the inequality

$$\mathrm{P}\left\{\sqrt{\frac{n}{\log n}}\,\|\phi_n-\phi\|_{L_\infty(\mathbb{R},w)}>\xi\right\} \;\le\; Bn^{-1-\delta'} \tag{43}$$

holds for any $\xi>\xi_0$ and some positive constant B depending on ξ.

Proof. Denote $\mathcal{W}_n(u)=\phi_n(u)-\mathbb{E}[\phi_n(u)]$. Consider the sequence $A_k=e^k,\; k\in\mathbb{N}$ and cover each interval $[-A_k,A_k]$ by $M_k=(\lfloor 2A_k/\gamma\rfloor+1)$ disjoint small intervals $\Lambda_{k,1},\ldots,\Lambda_{k,M_k}$ of the length γ. Let $u_{k,1},\ldots,u_{k,M_k}$ be the centers of these intervals. We have for any natural $K>0$

$$\begin{aligned}\max_{k=1,\ldots,K}\sup_{A_{k-1}<|u|\le A_k}|\mathcal{W}_n(u)| \;&\le\; \max_{k=1,\ldots,K}\max_{|u_{k,m}|>A_{k-1}}|\mathcal{W}_n(u_{k,m})| \\ &\quad+\max_{k=1,\ldots,K}\max_{1\le m\le M_k}\sup_{u\in\Lambda_{k,m}}|\mathcal{W}_n(u)-\mathcal{W}_n(u_{k,m})|.\end{aligned}$$

Hence

$$\begin{aligned}\mathrm{P}\left(\max_{k=1,\ldots,K}\sup_{A_{k-1}<|u|\le A_k}|\mathcal{W}_n(u)|>\lambda\right)\le \sum_{k=1}^{K}\sum_{\{|u_{k,m}|>A_{k-1}\}}\mathrm{P}(|\mathcal{W}_n(u_{k,m})|>\lambda/2)+ \\ \mathrm{P}\left(\sup_{|u-v|<\gamma}|\mathcal{W}_n(v)-\mathcal{W}_n(u)|>\lambda/2\right).\end{aligned} \tag{44}$$

It holds for any $u, v \in \mathbb{R}$

$$
\begin{aligned}
|\mathcal{W}_n(v) - \mathcal{W}_n(u)| &\leq 2|w(|v|) - w(|u|)| \\
&\quad + \frac{1}{n}\sum_{j=1}^{n} |\exp(\mathrm{i}vZ_j) - \exp(\mathrm{i}uZ_j)| + |\phi(v) - \phi(u)| \\
&\leq (u-v)\left[L_w + \frac{1}{n}\sum_{j=1}^{n}|Z_j| + \mathbb{E}|Z|\right], \qquad (45)
\end{aligned}
$$

where L_ω is the Lipschitz constant of w. The Markov inequality implies

$$
\mathrm{P}\left(\frac{1}{n}\sum_{j=1}^{n}[|Z_j| - \mathbb{E}|Z|] > c\right) \leq c^{-p} n^{-p} \mathbb{E}\left|\sum_{j=1}^{n}[|Z_j| - \mathbb{E}|Z|]\right|^p
$$

for any $c > 0$. Using now Dedecker and Rio inequalities and taking into account the assumptions (AZ1)-(AZ2), we get

$$
\mathbb{E}\left|\sum_{j=1}^{n}[|Z_j| - \mathbb{E}|Z|]\right|^p \leq C_p(\bar{\alpha}) n^{p/2},
$$

where $C_p(\bar{\alpha}_1)$ is some constant depending on $\bar{\alpha} = (\bar{\alpha}_0, \bar{\alpha}_1)$ and p from assumptions (AZ1) and (AZ2) respectively. Hence,

$$
\mathrm{P}\left(\frac{1}{n}\sum_{j=1}^{n}|Z_j| > 2 \cdot \mathbb{E}|Z|\right) \leq C_p(\bar{\alpha}) n^{-p/2} (\mathbb{E}|Z|)^{-p}. \qquad (46)
$$

Setting $\gamma = \lambda/(24 \max\{\mathbb{E}|Z|, L_w\})$ and combining (45) with the inequality (46), we obtain

$$
\mathrm{P}\left(\sup_{|u-v|<\gamma} |\mathcal{W}_n(v) - \mathcal{W}_n(u)| > \lambda/2\right) \leq B_1 n^{-p/2} \qquad (47)
$$

with some constant B_1 not depending on λ and n. Let us turn now to the first term on the right-hand side of (44). If $|u_{k,m}| > A_{k-1}$, then it follows from Theorem 6.1 and Corollary 6.2

$$
\begin{aligned}
&\mathrm{P}\left(|\operatorname{Re}[\mathcal{W}_n(u_{k,m})]| > \lambda/4\right) \\
&\qquad \leq B_2 \exp\left(-\frac{B_3 \lambda^2 n}{4w^2(A_{k-1})\log^{2(1+\varepsilon)}(w(A_{k-1})) + \lambda \log^2(n) w(A_{k-1})}\right),
\end{aligned}
$$

$$
\begin{aligned}
&\mathrm{P}\left(|\operatorname{Im}[\mathcal{W}_n(u_{k,m})]| > \lambda/4\right) \\
&\qquad \leq B_4 \exp\left(-\frac{B_3 \lambda^2 n}{4w^2(A_{k-1})\log^{2(1+\varepsilon)}(w(A_{k-1})) + \lambda \log^2(n) w(A_{k-1})}\right)
\end{aligned}
$$

with some constants B_2, B_3 and B_4 depending only on the characteristics of the process Z. Taking $\lambda = \zeta n^{-1/2}\log^{1/2} n$ with $\zeta > 0$, we get

$$\sum_{\{|u_{k,m}|>A_{k-1}\}} \mathrm{P}(|\mathcal{W}_n(u_{k,m})| > \lambda/2) \le (\lfloor 2A_k/\gamma\rfloor + 1)$$
$$\times \exp\left(-\frac{B_3\lambda^2 n}{4w^2(A_{k-1})\log^{2(1+\varepsilon)}(w(A_{k-1})) + \lambda\log^2(n)w(A_{k-1})}\right)$$
$$\lesssim A_k N^{1/2}\exp\left(-\frac{B\zeta^2\log(n)}{w^2(A_{k-1})\log^{2(1+\varepsilon)}(w(A_{k-1}))}\right)\log^{(r-1)/2}(n), \quad n\to\infty$$

with $r = 2(1+\varepsilon)$ and some constant $B > 0$. Fix $\theta > 0$ such that $B\theta > d$ and compute

$$\begin{aligned}\sum_{\{\|u_{k,m}\|>A_{k-1}\}} \mathrm{P}(|\mathcal{W}_n(u_{k,m})| > \lambda/2) \quad &\lesssim \quad e^{k-\theta B(k-1)} n^{1/2}\log^{(r-1)/2}(n) e^{-B(k-1)(\zeta^2\log n-\theta)}\\ &\lesssim \quad e^{k(1-\theta B)}\log^{(r-1)/2}(n) e^{-B(k-1)(\zeta^2\log n-\theta)+\log(n)}.\end{aligned}$$

a If $\zeta^2\log n > \theta$ we get asymptotically

$$\sum_{k=2}^{K}\sum_{\{\|u_{k,m}\|>A_{k-1}\}} \mathrm{P}(|\mathcal{W}_n(u_{k,m})| > \lambda/2) \quad \lesssim \quad \log^{(r-1)/2}(n) e^{-(B\zeta^2-1)\log(n)}.$$

Taking large enough $\zeta > 0$, we get (43). □

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