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Radner equilibrium in incomplete Lévy models

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Abstract

We construct continuous-time equilibrium models based on a finite number of exponential utility investors. The investors' income rates as well as the stock's dividend rate are governed by discontinuous Lévy processes. Our main result provides the equilibrium (i.e., bond and stock price dynamics) in closed-form. As an application, we show that the equilibrium Sharpe ratio can be increased and the equilibrium interest rate can be decreased (simultaneously) when the investors' income streams cannot be traded.

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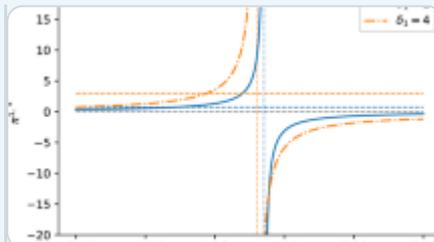
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$$\int_0^T \kappa^\ell q_N(Z^\ell) - e^{-\iota_N(a)} dt, \\ + e^{-\iota_N(a)} (1 + \iota_N(a) + \iota_N(\lambda))$$

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Notes

1. Theorem 4.1 in [8] shows that no model based on exponential utilities, continuous consumption, and a filtration generated by Brownian motions can ever produce an incompleteness impact on the Sharpe ratio when this ratio is measured instantaneously.
2. By restricting the investors to only consume at maturity, the economy's interest rate cannot be determined. Furthermore, by only considering financial

assets, the assets' volatility structures also remain undetermined. Therefore, the interest rate and the volatility parameters are taken as exogenously specified model input in such models.

3. As usual, the price dynamics of the money account are given by $(dS_t^{\{(0)\}} = r_t S_t^{\{(0)\}} dt)$ with $(S_0^{\{(0)\}} = 1)$.
4. The geometric form of this Lévy process was first used in finance by Merton in his classical paper [18]. This process is also the basis for Bates' asset pricing model developed in [3].
5. We will need to place various integrability restrictions on the investor's possible choices of $(\theta_i, \theta_i^{\{(0)\}}, c_i)$; see Definition 4.1 below.
6. Radner's equilibrium notion has a long history in financial economics and is also called security-spot market equilibrium. We refer to Section 10 in the textbook [10] for more details.
7. The process J will be related to the stock's dividend process D below.
8. The brackets $(\langle \cdot, \cdot \rangle)$ are also called the conditional quadratic cross variation; see, e.g., Section III.5 in [19].
9. The technical difficulties related to the existence of equivalent martingale measures on infinite time-horizons already arise in Black-Scholes' model; see, e.g., the textbook discussion in Section 6.N in [10]. The same technical issues are also present in our jump setting which is why we prefer to use martingale densities.
10. For continuous-time optimal control problems, martingale conditions are always needed to verify optimality (see, e.g., Section V.15 in the textbook

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Appendices

An auxiliary lemma

Lemma 6.1

Suppose Assumption [3.1](#) holds. Then the partial derivative

$$\begin{aligned} \varphi_i(u^{(0)}, u^{(i)}) &= \frac{\partial}{\partial u^{(0)}} \int_{\mathbb{R}^{I+1}} e^{u^{(0)}z^{(0)} + u^{(i)}z^{(i)}} \nu(dz), \quad u^{(0)}, u^{(i)} \in \mathbb{R}, \end{aligned}$$

(6.11)

is a well-defined function and satisfies the following properties:

1. The function φ_i has the representation

$$\begin{aligned} \varphi_i(u^{(0)}, u^{(i)}) &= \int_{\mathbb{R}^{I+1}} z^{(0)} e^{u^{(0)} z^{(0)} + u^{(i)} z^{(i)}} \nu(dz), \quad u^{(0)}, u^{(i)} \in \mathbb{R}. \end{aligned}$$

(6.12)

2. The function φ_i is jointly continuous.

3. For fixed $u^{(i)} \in \mathbb{R}$, the function $u^{(0)} \mapsto \varphi_i(u^{(0)}, u^{(i)})$ is strictly increasing and onto \mathbb{R} . Consequently, the inverse function $f_{i,u^{(i)}}(\cdot)$ exists and is continuous on \mathbb{R} .

Proof

For the first claim, we can use the bound

$$\begin{aligned} \frac{|e^{hz} - 1|}{|h|} \leq |z| e^{|z|}, \quad z \in \mathbb{R}, \quad |h| \leq 1. \end{aligned}$$

(6.13)

This bound is integrable by (3.2) and (3.3) of Assumption 3.1. Therefore, the dominated convergence theorem can be used to produce the representation (6.12). The second claim follows similarly. The strict monotonicity property in the last claim follows directly from (6.12). Finally, (3.4) ensures that the map $\varphi_i(\cdot, u^{(i)})$ is onto \mathbb{R} . \square

Proofs

Proof of Lemma 3.2

The integrability property

$$\begin{aligned} \int_{\mathbb{R}^{I+1}} \big(\psi(z)\big)^2 \nu(dz) < \infty, \end{aligned}$$

(6.14)

follows from the definition of ψ (see [3.12](#)), the bound [\(6.13\)](#), and the integrability requirements in Assumption [3.1](#). Furthermore, because ψ defined by [\(3.12\)](#) satisfies $\psi + 1 > 0$ we see from Theorem 37 in Section II.8 in [\[19\]](#) that there is a unique strictly positive solution Z of [\(3.11\)](#). The martingale property of Z follows from Novikov's condition for Lévy processes (see Theorem 9 in [\[20\]](#)). The claimed sigma-martingale property follows from Itô's product rule applied to $(Z \frac{S}{S^{(0)}})$ combined with the no drift property

$$\begin{aligned} \frac{\mu_r}{\sigma_D} + \int_{\mathbb{R}^{I+1}} \psi(z) z^{(0)} \nu(dz) = 0. \end{aligned}$$

(6.15)

The latter condition [\(6.15\)](#) follows from the definition of ψ . \square

Proof of Theorem 4.2

Throughout this proof we let (V_i) be defined by [\(4.5\)](#) and we let $(\theta_{i,c}^*)$ be defined by [\(4.4\)](#) and [\(4.9\)](#). We split the proof into two steps:

Step 1: (Admissibility of $(\theta_{i,c}^*)$). By inserting $(\theta_{i,c}^*)$ into [\(4.2\)](#) we produce the gain dynamics

$$\begin{aligned} dX_{it}^* = \Big(\theta_{i,c}^* \mu - \frac{\tau_{ig_i}}{r} \Big) dt + \theta_{i,c}^* \frac{\sigma_D}{r} \int_{\mathbb{R}^{I+1}} z^{(0)} \tilde{N}(dt, dz), \quad t \geq 0. \end{aligned}$$

(6.16)

To see that (X_{it}^*) has all exponential moments we let $(a \in \mathbb{R})$ be arbitrary. The integrability conditions [\(3.1\)](#) and [\(3.3\)](#) ensure that

$$\begin{aligned} \int_{\mathbb{R}^{I+1}} \left(e^{az^{(0)}} - 1 - az^{(0)} \right) \nu(dz) < \infty. \end{aligned}$$

(6.17)

Consequently, Itô's lemma ensures that

$$\begin{aligned} & e^{\int_0^t \int_{\mathbb{R}^{I+1}} z^{(0)} \tilde{N}(du, dz) - \int_{\mathbb{R}^{I+1}} (e^{az^{(0)}} - 1 - az^{(0)}) \nu(dz)} \end{aligned}$$

is a nonnegative sigma-martingale. Furthermore, Ansel and Stricker's Theorem ensures that it is a supermartingale which combined with the deterministic property of (6.17) produces

$$\begin{aligned} & \mathbb{E} \left[e^{\int_0^t \int_{\mathbb{R}^{I+1}} z^{(0)} \tilde{N}(du, dz)} \right] \leq e^{\int_{\mathbb{R}^{I+1}} (e^{az^{(0)}} - 1 - az^{(0)}) \nu(dz)} < \infty. \end{aligned}$$

(6.18)

In a similar fashion we can see that (Y_{it}) has all exponential moments. This shows that the expected utility of (θ^*_i, c^*_i) is finite.

To see that the stochastic integral (4.8) is a martingale, it suffices to show the square integrability property

$$\begin{aligned} & \mathbb{E} \left[\int_0^t \int_{\mathbb{R}^{I+1}} (X^*_{iu}, Y_{iu})^2 \int_{\mathbb{R}^{I+1}} (e^{-\frac{\theta_i^* \sigma_D}{\tau_i} z^{(0)} - \frac{\sigma_i}{\tau_i} z^{(i)}} - 1)^2 \nu(dz) du \right] < \infty, \end{aligned}$$

for all $t \geq 0$. The integrand in the (ν) -integral does not depend on $(\omega \in \Omega)$. The bound (6.13) combined with (3.1) and (3.3) ensures that this (ν) -integral is finite. Furthermore, the first inequality in (6.18) shows that the functions

$$\begin{aligned} & \{ \}_{[0, t]} \ni u \rightarrow \mathbb{E} \left[e^{bX^*_{iu}} \right] \quad \text{and} \quad [0, t] \ni u \rightarrow \mathbb{E} \left[e^{b'Y_{iu}} \right], \end{aligned}$$

are bounded by exponential functions for all $(b, b' \in \mathbb{R})$. Because such functions on finite intervals are bounded, the square integrability property follows from Cauchy-Schwartz's inequality.

To verify the transversality condition (4.7) we use Itô's lemma to compute the dynamics

$$\begin{aligned} dV_i(X^*_{it}, Y_{it}) &= \int_{\mathbb{R}^{I+1}} \Big(V_i(X^*_{it-} + \theta_i^* \frac{\sigma_D}{r} z^{(0)}, Y_{it-} + \sigma_{iz}^{(i)}) - \\ & V_i(X^*_{it-}, Y_{it-}) \Big) \tilde{N}(dt, dz) \quad \text{and} \quad + V_i(X^*_{it-}, Y_{it-}) \\ & \int_{\mathbb{R}^{I+1}} \left(\frac{1}{\tau_i} \left(\theta_i^* \sigma_{Dz}^{(0)} + \sigma_{iz}^{(i)} \right) + e^{-\frac{\theta_i^* \sigma_D}{\tau_i}} z^{(0)} - \frac{1}{\tau_i} \sigma_{iz}^{(i)} - 1 \right) \nu(dz) dt \quad \text{and} \\ & - V_i(X^*_{it-}, Y_{it-}) \int_{\mathbb{R}^{I+1}} \left(\frac{r}{\tau_i} \mu \theta_i^* - g_i + \frac{\mu_i}{\tau_i} \right) dt \\ & = \int_{\mathbb{R}^{I+1}} \Big(V_i(X^*_{it-} + \theta_i^* \frac{\sigma_D}{r} z^{(0)}, Y_{it-} + \sigma_{iz}^{(i)}) - \\ & V_i(X^*_{it-}, Y_{it-}) \Big) \tilde{N}(dt, dz) \quad \text{and} \\ & + V_i(X^*_{it-}, Y_{it-}) \int_{\mathbb{R}^{I+1}} (\delta_i - r) dt. \end{aligned}$$

The just proven martingale property of the stochastic integral (4.8) produces

$$\begin{aligned} \mathbb{E}[V_i(X^*_{it}, Y_{it})] &= V_i(X_{i0}, Y_{i0}) + \int_0^t \mathbb{E}[V_i(X^*_{iu}, Y_{iu})] (\delta_i - r) du. \end{aligned}$$

Therefore, because $(r > 0)$, we have

$$\begin{aligned} \lim_{t \rightarrow \infty} e^{-\delta_i t} \mathbb{E}[V_i(X^*_{it}, Y_{it})] &= \lim_{t \rightarrow \infty} e^{-\delta_i t} V_i(X_{i0}, Y_{i0}) e^{(\delta_i - r)t} = 0. \end{aligned}$$

(6.19)

Step 2 (Verification): Itô's lemma produces the following dynamics for arbitrary controls $((\theta_i, c_i) \in \mathcal{A}_i)$

$$\begin{aligned}
& d\left(\int_0^t e^{-\delta_i u} U_i(c_{iu} + Y_{iu}) du + e^{-\delta_i t} V_i(X_{it}, Y_{it}) \right) \\
& \quad = e^{-\delta_i t} \Bigg\{ U_i(c_{it} + Y_{it}) dt - \delta_i V_i(X_{it}, Y_{it}) dt \\
& \quad \quad + \int_{\mathbb{R}^{I+1}} \left(V_i(X_{it-} + \theta_{it} \frac{\sigma_D}{r} z^{(0)}, Y_{it-} + \sigma_{iz}^{(i)}) - V_i(X_{it-}, Y_{it-}) \right) \tilde{N}(dt, dz) \\
& \quad \quad + V_i(X_{it-}, Y_{it-}) \int_{\mathbb{R}^{I+1}} \left(\frac{1}{\tau_i} \left(\theta_{it} \sigma_{Dz}^{(0)} + \sigma_{iz}^{(i)} \right) + e^{-\frac{\theta_{it} \sigma_D}{\tau_i} z^{(0)} - \frac{1}{\tau_i} \sigma_{iz}^{(i)}} - 1 \right) \nu(dz) dt \\
& \quad \quad - V_i(X_{it-}, Y_{it-}) \frac{r}{\tau_i} \left(r X_{it-} - c_{it} + \mu \theta_{it} \right) dt - V_i(X_{it-}, Y_{it-}) \frac{\mu_i}{\tau_i} dt \Bigg\}.
\end{aligned}$$

A direct calculation shows that the drift is maximized pointwise by the processes (θ_i^*, c_i^*) given by (4.4) and (4.9). Furthermore, the definition of (g_i) ensures that this maximal value is zero. Therefore, the martingale property of the integrals in (4.8) produces

$$\begin{aligned}
& \mathbb{E} \left[\int_0^t e^{-\delta_i u} U_i(c_{iu} + Y_{iu}) du + e^{-\delta_i t} V_i(X_{it}, Y_{it}) \right] \\
& \quad \leq V(X_{i0}, Y_{i0}) \\
& \quad = \mathbb{E} \left[\int_0^t e^{-\delta_i u} U_i(c_i^* + Y_{iu}) du + e^{-\delta_i t} V_i(X_{it}^*, Y_{it}) \right].
\end{aligned}$$

We can then use the monotone convergence theorem to pass $(t \rightarrow \infty)$ as well as the transversality condition (4.7) to see

$$\begin{aligned}
& \mathbb{E} \left[\int_0^\infty e^{-\delta_i u} U_i(c_{iu} + Y_{iu}) du \right] \leq V(X_{i0}, Y_{i0}) = \mathbb{E} \left[\int_0^\infty e^{-\delta_i u} U_i(c_i^* + Y_{iu}) du \right].
\end{aligned}$$

\square

Proof of Theorem 5.1

Fix the time points $(0 \leq t \leq s < \infty)$. Based on Lemma [3.2](#) we can define the (\mathbb{P}) -equivalent measure (\mathbb{Q}_s) on (\mathcal{F}_s) by the Radon-Nikodym derivative $(\frac{d\mathbb{Q}_s}{d\mathbb{P}} := Z_s)$. Girsanov's theorem and the definition of (ψ) (see [3.12](#)) produce the (\mathbb{Q}_s) -dynamics

$$\begin{aligned} dD_u &= (\mu_D - \mu_r) du + \sigma_D \int_{\mathbb{R}^{I+1}} z^{(0)} \Big(N(du, dz) - \big(1 + \psi(z)\big) \nu(dz) \Big), \quad u \in [0, s]. \end{aligned}$$

To ensure that the stochastic integral is a (\mathbb{Q}_s) -martingale it suffices to show

$$\int_{\mathbb{R}^{I+1}} (z^{(0)})^2 \big(1 + \psi(z)\big) \nu(dz) < \infty.$$

This follows from (ψ) 's definition ([3.12](#)) and the integrability requirements in Assumption [3.1](#). Bayes' rule then produces

$$\begin{aligned} \begin{aligned} \frac{\mathbb{E}[Z_s D_s | \mathcal{F}_t]}{Z_t} &= \mathbb{E}^{\mathbb{Q}_s}[D_s | \mathcal{F}_t] = D_t + (\mu_D - \mu_r)(s-t). \end{aligned} \end{aligned}$$

(6.20)

This gives us the representation

$$\begin{aligned} \begin{aligned} S_t &= \int_t^\infty e^{-r(s-t)} \frac{\mathbb{E}[Z_s D_s | \mathcal{F}_t]}{Z_t} ds = \frac{D_t}{r} + \frac{\mu_D - \mu_r}{r^2}. \end{aligned} \end{aligned}$$

(6.21)

This representation and ([3.7](#)) produce the dynamics ([3.9](#)).

To see that the clearing conditions (2.3) hold, we first note that by inserting (μ) defined by (5.4) into (5.2) gives us (4.4); hence, (θ^*_i) is optimal by Theorem 4.2. Therefore, we have

$$\begin{aligned} \sum_{i=1}^I \theta^*_i &= -\frac{1}{\sigma_D} \sum_{i=1}^I \tau_i \frac{1}{\sigma_i} \left(-\frac{\mu_r}{\sigma_D} + \int_{\mathbb{R}^{I+1}} z^{(0)} \nu(dz) \right) = 1, \end{aligned} \quad (6.22)$$

where the last equality follows from inserting (μ) defined by (5.4) into (5.1). Clearing for the money market account is equivalent to $(S_t = \sum_{i=1}^I X^*_{it})$. For $(t=0)$ this holds. By inserting the optimal consumption processes (4.9) into the gain dynamics (4.2) and using the already established property $(\sum_{i=1}^I \theta^*_i = 1)$ we find

$$\begin{aligned} \sum_{i=1}^I dX^*_{it} &= \left(\mu - \sum_{i=1}^I \frac{\tau_{ig_i}}{r} \right) dt + \frac{\sigma_D}{r} \int_{\mathbb{R}^{I+1}} z^{(0)} \tilde{N}(dt, dz). \end{aligned}$$

On the other hand, the representation (6.21) produces

$$dS_t = \frac{\mu_D}{r} dt + \frac{\sigma_D}{r} \int_{\mathbb{R}^{I+1}} z^{(0)} \tilde{N}(dt, dz).$$

The claim therefore follows as soon as we establish

$$\sum_{i=1}^I \tau_i g_i = \mu_r - \mu_D. \quad (6.23)$$

To see that this relationship holds we can insert the definition of (g_i) (see 4.6) and use the definition of r (see 5.3). This argument also produces clearing in the good's market because

$$\sum_{i=1}^I c_{it}^* = \sum_{i=1}^I \text{Big}(rX^*_{it} +$$

$$\frac{\tau_{ig_i}\{r\}}{\text{Big}} = rS_t + \sum_{i=1}^I \frac{\tau_{ig_i}\{r\}}{\text{Big}} = D_t + \frac{\mu_D - \mu_r}{r} + \sum_{i=1}^I \frac{\tau_{ig_i}\{r\}}{\text{Big}} = D_t.$$

Here the third equality follows from the representation (6.21) and the last equality comes from (6.23). \square

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