Loss Aversion and Market Crashes

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This study proposes a rational expectation equilibrium model of stock market crashes with information asymmetry and loss averse speculators. We obtain a state-dependent linear optimal trading strategy, which makes the equilibrium price tractable. The model predicts nonlinear market depth and the result that small shocks to fundamentals (e.g., supply or informational shocks) can cause abrupt price movements. We demonstrate that short-sale constraints intensify asset price collapses relative to upward movements. The model also generates contagion between uncorrelated assets. These results are consistent with the main puzzling features observed during market crashes, namely abrupt and asymmetric price movements that are not driven by major news events but coupled with a spillover effect between unrelated markets.

Key words: contagion; information asymmetry; loss aversion; market crashes; short-sale constraints

JEL Classification: D03, D82, G11, G12, G41

1. Introduction

Economists find it difficult to rationalize the growing number of local stock market crashes leading to widespread turbulence in the global capital market. It is now widely agreed that macroeconomic shocks cannot be held entirely responsible for the recent stock market turmoil. Since the 2008 global financial crisis, markets have continued to suffer from severe turbulence. Examples include the European sovereign debt crisis of 2009-2012, the Russian financial crisis of 2014-2015, the Brazilian economic crisis of 2014-2016, the Chinese stock market crash of 2015, the US stock market correction in early 2018, and the recent COVID-19 pandemic-related market crash, showing the four largest ever intra-day drops in the S&P 500 between March 9, 2020 and March 16, 2020.

There is some consensus in the literature\(^1\) about the definition of “crash”. A crash should include the following three striking features, most generally observed during times of market disturbance:

1. Large movements in stock price without a correspondingly large public news event

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\(^1\) See Hong and Stein (2003) and Yuan (2005).
2. More severe average downward price movements than equivalent upward price movements

3. Financial contagion (shock spillover between fundamentally unrelated securities or markets)

While interpretation of the above features remains puzzling, constrained information asymmetry frameworks can provide them at least partial support. This encouraged us to develop a tractable equilibrium with asymmetric information to investigate the relationship between loss aversion and market crashes. The theory we propose predicts the above phenomena. We find that speculators’ loss aversion might be a major cause of market turmoil, accompanied by financial contagion. Despite the tremendous effort devoted to applying loss aversion to finance problems, no previous theoretical work has investigated the intuitive relationship that might exist between a market meltdown and loss aversion. We believe it is important to fill this gap.

Until recently, behavioral models of information asymmetry in financial markets focused mostly on economies where traders are overconfident. Only Pasquariello (2014) proposes one with prospect theory preferences. Specifically, he highlights the impact of speculators’ loss aversion on market quality. In our setting, we assume that speculator preferences are not dictated to by prospect theory (Kahneman and Tversky 1979; Tversky and Kahneman 1992) but rather by the theory of von Gaudecker et al. (2011). In our model, speculator preferences augment the standard exponential utility function with the loss aversion preferences.

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2 Benartzi and Thaler (1995) apply loss aversion in order to provide a theoretical explanation of the equity premium puzzle; Odean (1998b) finds that individual investors are reluctant to realize losses; Barberis et al. (2001) find that stock returns have a high mean, are excessively volatile and are significantly predictable, and in line with observations of historical data; Genesove and Mayer (2001) show that house sellers are unwilling to sell below the buying price; Gomes (2005), and Berkelaar et al. (2004) find that investors abstain from holding stocks unless they expect the equity premium to be high; Dittmann et al. (2010) explain observed compensation practices, given certain assumptions. Pasquariello (2014) explains patterns related to liquidity and price efficiency. More recently, Easley and Yang (2015) document the impact on investor’s survival prospect.

3 Kyle and Wang (1997) show that overconfident traders survive in the long run. Benos (1998), and Odean (1998a), show that overconfidence leads to higher trading volume, volatility, and liquidity. Daniel et al. (1998) demonstrate that overconfidence coupled with self-attribution bias might cause investors to overreact and destabilize prices. Ko and Huang (2007), Garcia, Sangiorgi, and Urošević (2007) mitigate these accepted findings on market quality slightly, showing that the overconfidence bias does not affect negatively informational efficiency, while in certain circumstances, overconfidence may even push traders to overinvest in private information, and to improve market pricing.

4 We share similar implications on market quality with Pasquariello’s (2014) paper, like state dependence of the optimal demand, or the volatility and volume (unreported results). However, the very purpose of the paper is to develop a theory of crash, rather than analyzing market quality implications.
parameter, and assume the same type of curvature on gains and losses, which makes them much less complex to include in the model than prospect theory preferences. Besides their ability to capture loss aversion, it is mainly due to the properties they share with the standard exponential utility function, and the difficulty of avoiding approximation when deriving market equilibrium with asymmetric information under non-standard (or exponential) CARA preferences.\footnote{Peress (2004) documents the assumption of CARA preferences in standard noisy rational expectations model. He successfully departs from it, using small risk approximation, making it possible, therefore, to capture the wealth effect.} Our rational expectation equilibrium model of crashes departs also obviously from Pasquariello (2014) economy since we introduce short-sale constraints and multiple risky assets to study asymmetries in the dynamic of returns, and contagion between a priori unrelated markets, respectively.

The model we develop is a noisy rational expectation equilibrium model à la Grossman and Stiglitz (1980) in which competitive price-taking, loss-averse speculators endowed with private information maximize their expected utility, trading with liquidity traders and risk-neutral uninformed market makers (MMs). We obtain a closed-form characterization of the non-linear equilibrium, and a state-dependant linear optimal trading strategy, where loss aversion restrains speculators from trading for weak signals. Trading intensity within the trading-region only remains unchanged in comparison to risk averse speculators, which makes MMs’ inference problem tractable for the first time in an economy with informed loss averse traders. It permits to highlight MMs’ confusion phenomenon and demonstrate how small trigger shocks from noise traders or insignificant news events can create large price movements in the intermediate price region.\footnote{While Pasquariello’s (2014) paper has the merit, unlike ours, to consider risk seeking in gains, an important feature of prospect theory, this first result can hardly be derived from it where equilibrium price is state dependent and approximated using OLS. Our model however, leading to the equilibrium permits to highlight among others, the confusion mechanism. This represents the cornerstone of this study, for the development of the crash model.} It is also consistent with evidence reported by Cutler et al. (1989), according to which both crashes and market bubbles appear without any preceding public news.\footnote{This result is consistent with earlier works of Roll (1984, 1988)\cite{Roll:1988} and French and Roll (1986) where they demonstrate in various ways that it is difficult to explain asset price movements with tangible public information.} They appear when the absolute value of the aggregate order flow is low. In that state, market makers feel extremely confused about the
trading regime of informed traders, and so the market depth becomes non-linear. Typically, asset collapses occur when the market depth is low.

In a second stage, we extend the model to incorporate short-sale constraints. The unique interaction between loss aversion and short-sales produces asymmetric price movements. Short-sale restriction makes high prices reveal less information than low prices, and produces asymmetric price movements, as reported in the literature (see, e.g., Pindyk 1984; French et al. 1987; Bekaert and Wu 2000; Yuan 2005). Specifically, prices are more likely to fall than to rise. In other words, we show that, unlike under certain restrictive conditions, in which both risk aversion and the number of traders that cannot sell short are very low, markets melt down more often than they melt up.\(^8\) When we analyze historical stock return data, we observe that the net change of eight of the ten largest one-day movements of the S&P 500 since 1947 were declines. Thus, from a regulatory perspective, the presence of short-sale constrained, better-informed, loss-averse traders mitigates the effectiveness of bans on short sales defended by regulators, which are very often imposed in times of market stress. This is indeed consistent with Beber and Pagano's (2013) evidence that short-selling bans were detrimental to liquidity, slowed price discovery, and failed to support prices.

Finally, we extend the proposed model to multiple assets, showing a contagion effect between uncorrelated assets. In other words, we highlight how idiosyncratic shocks unique to one market affect asset prices in other markets. We demonstrate this formally for the optimal demand of informed traders. Following a news event concerning one asset, loss-averse informed traders might refrain from trading assets in a portfolio consisting only of uncorrelated assets. Unfortunately, the inference problem for the equilibrium price in a multiple-risky-assets economy becomes intractable. We provide numerical approximation in a two-risky-asset economy and demonstrate that contagion occurs. Namely, that small news event in one market might create substantial price movement in another uncorrelated market. This spillover mechanism is the third acknowledged feature of market crashes. The fact that crashes appear to

\(^8\) We check for negative skewness in economies where the risk aversion is much greater than other technology parameters, or which have a short-selling ban or a high level of short sales.
be contagious is supported by the empirical observation that the correlation between assets increases sharply in falling markets and cannot often be explained by fundamentals.⁹

The literature on stock market crashes involving trading constraints often attributes such crashes to either increased or reduced uncertainty. The models developed by Romer (1993), Cao et al. (2002), ascribe crashes to constrained traders for whom uncertainty is suddenly resolved, bringing prices closer to fundamental values. However, the models of Barlevy and Veronesi (2003), Yuan (2005), and Marin and Olivier (2008) do not accredit crashes to any release of information, but on the contrary, to sharp increase in uninformed traders’ uncertainty with regard to fundamentals. Our model blurs this distinction. Market meltdown arises principally because speculators’ optimal demand is partially non-revealing when uninformed traders’ uncertainty is high, but when the release of trivial information might suddenly solve the market makers’ inference problem, causing prices to collapse. Our setting is closer to the rational expectation equilibrium models of Barlevy and Veronesi (2003), and Yuan (2005), than to that of Marin and Olivier (2008). Unlike these authors, we do not make informed-investor trading observable by all market participants. Rather, uninformed traders constantly speculate on the constraint status of insiders. However, our model departs also from the models of Barlevy and Veronesi (2003) and Yuan (2005) in that high prices are not necessarily more informative than low prices.

The analysis presented in this paper is also related to the work of Ozsoylev and Werner (2011), Condie and Ganguli (2011) and, Mele and Sangiorgi (2015). Using a rational expectation equilibrium framework, they study how ambiguity (Knightian uncertainty (Knight, 1921)) over fundamentals affects asset prices. Typically, these papers, based on the standard Grossman and Stiglitz (1980) model, assume that markets are subject to ambiguity and that it is impossible to quantify the risky payoff probabilistically. Like loss

⁹ In this paper, we do not attempt to develop an exhaustive theory of contagion between financial assets, since many channels might explain this phenomenon (Kaminsky et al., 2003). Instead, we include multiple assets to attempt to produce a unifying theory of crash from a behavioral perspective that robustly explains its three striking features of market crashes. As stated, these are strong price variations without major news events, asymmetrical upward and downward movements, and contagion between apparently uncorrelated assets. One limitation of our model is however that unfortunately, the contagion effect is symmetrical and practical limitations of our model prevent us to introduce short-sale constraints in a two risky asset economy.
aversion, ambiguity aversion is a robust, well-documented behavioral bias. As in our study, Ozsoylev and Werner (2011), and Mele and Sangiorgi (2015) incorporate a noisy supply in their model and induce partial revelation of information. Whereas in our model, substantial price movements follow insignificant supply or informational shocks, Ozsoylev and Werner (2011), Condie and Ganguli (2011), and Mele and Sangiorgi (2015) show how large price swings occur after a small change in the uncertainty parameters.

The remainder of this paper is organized as follows. In section 2, we present a theoretical model of trading between loss averse speculators, market makers, and noise traders. We derive optimal demand, equilibrium price and market depth for our economy. We then perform comparative statics. Section 3 introduces short-sale constraints, and we obtain the asymmetry between downward and upward price movement. In Section 4, we extend the model to multiple risky assets and derive the contagion between two uncorrelated assets. Finally, Section 5 concludes and proposes avenues for further research.

2. The Trading Model

In this section, we describe a noisy Rational Expectation Model (REE) of sequential trading in the presence of better informed, loss averse speculators. Like Grossman and Stiglitz (1980), Diamond and Verrecchia (1981) and Vives (1995a), we assume that speculators are competitive, submit limit orders instead of market orders and that all random variables are normally distributed. Our model departs moderately from the Constant-Absolute-Risk-Aversion (CARA) Normal model. It incorporates a loss aversion parameter in the utility function while assuming the same type of curvature in gains and losses.

2.1 The Basic Economy

The economy is populated with informed traders, liquidity (“noise”) traders whose demand is exogenous and who trade for idiosyncratic lifecycle or liquidity reasons, and risk-neutral competitive market makers (MMs).10 Informed traders are competitive and form a continuum with measure one. The model includes

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10 We assume that the preferences of every trader, the structure of economy and the decision process leading to order flows are common knowledge.
two dates, time 0 and time 1. At time 0, investors trade competitively in the market based on their private information. At time 1, they realize payoffs from the assets and consumption occurs.

There is one risk-free asset and one risky asset. The risk-free asset is a claim to one unit of terminal-period wealth, and the risky asset pays \( v \) units of the single consumption good. While taking the risk-free asset to be the numeraire, we let \( P \) be the price for the risky asset. Prior to trading, informed investors receive private information related to the payoff of the risky asset. The signal \( s \) is a noisy signal of the asset final payoff \( v \), given \( s = v + \varepsilon \). We assume that all the informed investors receive the same private signal \( s \).\(^{11}\) We assume the random variables \( v \) and \( \varepsilon \) to be mutually independent and normally distributed with mean zero\(^{12}\) and variance \( \sigma_v^2 \) and \( \sigma_\varepsilon^2 \). Liquidity (“noise”) traders produce a random, normally distributed demand \( z \) with mean zero and variance \( \sigma_z^2 \). Moving first, liquidity traders submit market orders and speculators submit demand schedules or generalized limit orders to the MMs,\(^{13}\) contingent on their information before the equilibrium price \( P \) is set. When speculators optimize their demand, they consider the relation between the functional equilibrium price and the random variables in the economy. Then, competitive, risk neutral MMs set the price efficiently, given the observed aggregate order flow. We know that in large markets, competitive noisy rational equilibria are implementable, thus allowing agents to use demand schedules as strategies. As in Vives (1995a) and Pasquariello (2014) we denote a speculator demand schedule by \( x_i(s,.) \). Thus, when the price is \( P \), the desired position of the informed trader is \( x_i(s,P) \). We assume that the speculator perceives the investment of all her initial wealth \( W_{i,0} \) in the risk-free asset as the reference point, and any other outcomes as changes or profits with respect to this reference point.

\(^{11}\) We assume that speculators observe identical signals and have identical preferences. A model with diverse signals and/or diverse preferences is much more complicated and cannot derive a tractable equilibrium.

\(^{12}\) We assume, to save on notation, that the mean of \( v \) is zero. However, for the general value of \( E[v] \) the derivation remains the same for \( v - E[v] \).

\(^{13}\) Vives (1995b) suggests an equivalent yet more intuitive way to describe the market clearing process by referring to the notion of simultaneous placement of orders to a centralized auctioneer (CA) (see also Yuan (2005), and Ozsoylev and Werner (2011)).
point. Since we assume that the risk-free rate is zero, speculator \( i \) perceives the reference point as \( W_{i,0} \). So, the profits at time 1, from speculator \( i \), are given by \( \pi_i = x_i(v - P) \).

### 2.1.1 Loss Averse Speculators

Since the introduction of the Allais paradox (Allais, 1953) several authors have documented violations of the basic expected utility theory. Camerer's (2000) review of the literature finds that one particularly persistent empirical finding is a greater sensitivity to losses than to similar size gains. This idea that people are loss averse with respect to changes in wealth is a central feature of prospect theory (Kahneman and Tversky 1979). Recently, von Gaudecker et al. (2011) have analyzed risk preferences using an experiment with real incentives in a representative sample of 1,422 respondents. They find that utility curvature and loss aversion are the key determinants of individual choices under risk. We adopt the utility specification of von Gaudecker et al. (2011) to model speculators’ preferences.

\[
U(\pi, \lambda, \gamma) = \begin{cases} 
-\frac{1}{\gamma} e^{-\gamma\pi} & \text{for } \pi \geq 0 \\
\frac{\lambda}{\gamma} - \frac{\lambda}{\gamma} e^{-\gamma\pi} & \text{for } \pi < 0 
\end{cases}
\]

where \( \lambda > 1 \) represents the degree of loss aversion and \( \gamma > 0 \) is the coefficient of absolute risk aversion. In our model, all speculators, have the same utility function \( U(\pi, \gamma, \lambda) \), so we drop the subscripts \( i \).

The “CARA Normal” model is very popular. In various settings, it admits linear equilibria derived in a closed form.\(^{14}\) The objective of our preference choice is to maintain as much as we can of its modeling features, while successfully introducing loss aversion. The kink at the origin of \( U(\pi, \gamma, \lambda) \), with a steeper slope for losses than for gains, represents our only departure from CARA. This functional form, plotted in Fig. 1, disentangles preference parameters from utility curvature (risk aversion) and loss aversion.

\(^{14}\) See, e.g., Hellwig (1980), Grossman and Stiglitz (1980), Diamond and Verrecchia (1981), Admati (1985) and Vives (1995a).
Fig. 1 Utility function

Note: In line with loss aversion, this function exhibits a kink at its origin. The starred line represents one with a loss aversion parameter of $\lambda = 2.5$ and the crossed line represents the case when $\lambda = 1$, (CARA preferences). The risk aversion parameter is $\gamma = 1$.

Although prospect theory considers the utility function as concave over gains and convex over losses,\(^{15}\) Equation (1) assumes concavity over gains as well as losses.\(^{16}\) In their web appendix, von Gaudecker et al. (2011) compare the proposed specification with prospect theory specification and report slightly larger values of $\lambda$ for prospect theory preferences. They consider this as a mechanical consequence of different assumptions with regard to the shape of the utility function in the negative domain. For high-incentive treatment, they report a median estimate parameter of loss aversion of 2.38, in line with previous estimates.\(^{17}\)

\(^{15}\) The functional form is proposed in Tversky and Kahneman (1992) based on experimental findings.

\(^{16}\) Recent empirical evidence challenges prospect theory’s original utility function for mixed gamble (Baltussen et al. 2006). Moreover, von Gaudecker et al. (2011) show that changing the assumption curvature to prospect theory-type preferences does not substantially affect their main estimates.

\(^{17}\) The authors demonstrate that despite Köbberling and Wakker’s (2005) definition of loss aversion being model independent, the measurement parameters depend on the complete structure of the utility function. It is thus not possible to compare the parameters directly across models. In this study, we analyze the effect of loss aversion on the price formation process, and Coval and Shumway (2005) report in their empirical study, that the degree of loss
2.1.2 The Optimal Demand of Informed Traders

Let \( x(s,.) \) represent the demand schedule for the risky asset of an informed trader given private signal \( s \). When the price realization is \( P \), the demand function is then \( x(s,P) \). The only information available to the informed trader at time 0 is the noisy signal \( s \). Speculators neither learn from market price nor strategically anticipate how they demand will affect equilibrium price. Thus, the demand of the informed trader submitted at time 0, is given by the maximization of the expected utility

\[
E(U(\pi,\gamma,\lambda)|s) = -\frac{1}{\gamma} \left[ e^{-\gamma(\mu_{vs}-P)^2/2\sigma_{vs}^2} \left( 1 + (\lambda - 1)\Phi(\text{sgn}(x)\frac{x\sigma_{vs}^2}{\sigma_{vs}} - (\mu_{vs} - P)\frac{\sigma_{vs}}{\sigma_{vs}}) \right) \right] - (\lambda - 1)\Phi(\text{sgn}(x)\frac{\mu_{vs} - P}{\sigma_{vs}})
\]

where \( \mu_{vs} = \rho^2 s \) and \( \sigma_{vs} = \sigma_v\sqrt{1 - \rho^2} \) is the conditional mean and variance of the random risky payoff \( v \) given the private signal received by each speculator and where \( \rho = \frac{\sigma_v}{\sqrt{\sigma_v^2 + \sigma_e^2}} \). \( \Phi(.) \), refers to the cumulative distribution function of the standard normal distribution and \( \text{sgn}(x) \) is the sign function.\(^{18}\)

We present the derivation of Equation (2) and of the conditional mean and variance in the appendix. Equation (2) admits for each region (either positive demand or negative demand) only one bounded maximum value, since, as we will see in the ensuing analysis, the first-order condition of Equation (2) is solved for at most one value in each region. For unbounded values of \( x \) in each region, the objective function is equal to minus infinity.

Taking the first order condition of Equation (2) with respect to \( x \), yields

\[
\text{sgn}(x) = \begin{cases} 
1, & \text{if } x > 0 \\
0, & \text{if } x = 0 \\
-1, & \text{if } x < 0
\end{cases}
\]

\(^{18}\) aversion might vary across investors depending on prior gains and losses. Thus, since the model is static, one might consider an appropriate degree of loss aversion depending on market conditions. Moreover, Merkle (2020) shows that the impact on loss aversion is more pronounced for anticipated outcomes, when evaluating experienced returns, the effect diminishes by more than half.
Whether each speculator would engage in short or long position, the term in the bracket of Equation (3) should be equal to zero since the exponential function \( e^{-\gamma(x(\mu_{VLS}-P))} \) is bounded below by a positive number. Dividing both sides of Equation (3) by \( \gamma \sigma_{vl}s \) and defining \( \Lambda = x\gamma \sigma_{vl}s - \frac{\mu_{vl}s + P}{\sigma_{vl}s} \), we obtain

\[
\Lambda (1+(\lambda-1)\Phi(\text{sgn}(x)\Lambda)) + \text{sgn}(x)(\frac{\lambda-1}{2})e^{-\frac{1}{2}\Lambda^2} = 0. \tag{4}
\]

For any degree of loss aversion (\( \lambda \geq 1 \)), one can solve Equation (4) for \( \Lambda^* \) numerically. The proof of its existence and uniqueness has been relegated to the appendix. For example, if we set \( \lambda = 2 \) we find that \( \Lambda = -0.276 \) for a positive value of \( x \) and \( \Lambda = 0.276 \) for a negative value of \( x \). Thus, the optimal positive demand is \( x = \frac{\mu_{vl}s - P}{\gamma \sigma_{vl}s} + 0.276 \), and the optimal negative demand is \( x = \frac{\mu_{vl}s - P}{\gamma \sigma_{vl}s} - 0.276 \). We notice however that a positive or negative demand will depend on the magnitude and the precision of the private signal. In order to make demand positive, the signal should be relatively high, i.e. \( s \geq \frac{P + 0.276 \sigma_{vl}s}{\rho^2} \), and inversely, to make the demand negative, the signal should be relatively low, i.e. \( s < \frac{P - 0.276 \sigma_{vl}s}{\rho^2} \). Outside this range, in the interval \( |\mu_{vl}s - P| \leq 0.276 \sigma_{vl}s \) we note that neither the objective function for a positive value of \( x \) nor that for a negative value of \( x \) admits a local minimum, and thus, \( x = 0 \) maximizes the expected utility. The next proposition generalizes the solution of Equation (4) to any value of \( \lambda \) equal to or greater than 1, and is expressed as a function of \( \lambda \) \( (\Lambda = \Lambda(\lambda)) \).

**Proposition 1.** In the economy described above, the optimal demand for the loss averse informed trader is given by
\[ x_{LA}^* = \begin{cases} \frac{\rho^2 s - P}{\gamma \sigma_v^2 (1 - \rho^2)} - \frac{\Lambda(\lambda)}{\gamma \sigma_v \sqrt{1 - \rho^2}} & \text{for } s > \frac{P + \Lambda(\lambda) \sigma_v \sqrt{1 - \rho^2}}{\rho^2} \\ 0 & \text{elsewhere} \\ \frac{\rho^2 s - P}{\gamma \sigma_v^2 (1 - \rho^2)} + \frac{\Lambda(\lambda)}{\gamma \sigma_v \sqrt{1 - \rho^2}} & \text{for } s \leq \frac{P - \Lambda(\lambda) \sigma_v \sqrt{1 - \rho^2}}{\rho^2} \end{cases} \] (5)

where \( \Lambda = \Lambda(\lambda) \) solves \( \Lambda \left( 1 + (\lambda - 1) \Phi(-\Lambda) \right) - \frac{(\lambda - 1)}{\sqrt{2\pi}} e^{-\frac{1}{2} \lambda^2} = 0 \)

Fig. 2 plots the functional form \( \Lambda(\lambda) \) for loss aversion parameters in the range \([1, 10]\). From Fig. 2 we see that \( \Lambda(\lambda) \) is concave and increases with \( \lambda \).

**Fig. 2. The Functional Form of \( \Lambda(\lambda) \)**

Note: The graph plots the solution of Equation \( \Lambda \left( 1 + (\lambda - 1) \Phi(-\Lambda) \right) - \frac{(\lambda - 1)}{\sqrt{2\pi}} e^{-\frac{1}{2} \lambda^2} = 0 \) as a function of \( \lambda \).

We notice that for \( \lambda = 1 \), \( \Lambda(\lambda) = 0 \), and the optimal demand falls to the optimal generalized limit order under the regular CARA-Normal model with negative exponential utility (see, e.g., Vives 1995a; Grossman and Stiglitz, 1980).
Optimal demand is therefore a state-dependant linear function of the private signal and the equilibrium price. As for the standard CARA-Normal setting, the proposed model predicts that informed traders submit cautious limit orders. Loss aversion however prevents speculators from trading at all for a sufficiently weak signal in terms of absolute value.

Trading intensity (Vives, 1995a) is defined as the sensitivity of speculators’ demand function to information shocks $\zeta = \frac{\partial x}{\partial \zeta}$. In our model trading intensity is

$$
\zeta = \begin{cases} 
0 & \text{for } |s - \Delta| \leq \frac{P}{\rho^2} \\
\frac{1}{\gamma \sigma_x^2} & \text{for } |s - \Delta| > \frac{P}{\rho^2} 
\end{cases}
$$

where $\Delta(\lambda, \sigma_x, \sigma_z) = \frac{\Lambda(\lambda)\sigma_x\sqrt{1-\rho^2}}{\rho^2}$.

Increasing loss aversion or increasing risk aversion increases the cautiousness of the trade. The losses induced by trading, which obviously increase in proportion to the speculator’s loss aversion, are reflected in a reduction of optimal trading activity compared with risk averse speculators only. Outside the no-trade interval, the measure of loss averse trading aggressiveness is the same as for the standard CARA-normal model, depending solely on the precision of the private signal and on risk tolerance. In our model, since we disentangle risk aversion and loss aversion in speculators’ preferences, loss aversion does not affect the trading intensity for sufficiently large signals. Intuitively, an infinitesimal informational shock does not increase the likelihood of expected losses but affects the distribution of gains (change in final wealth). Thus, if speculators already trade on their private information, the degree of loss aversion should not impact trading intensity while risk aversion should.
2.2 Equilibrium

We now describe equilibrium prices and trading behavior in the model. MMs set the market clearing price from their expectation of the asset payoff $v$ conditional on the aggregate order flow realization $\omega = x + z$, according to semi-strong market efficiency.

$$
P(\omega) = E[v|\omega].$$

(8)

Risk neutrality and dealership competition imply the semi-strong market efficiency rule expressed by Equation (8).\(^{19}\) The MMs earn zero expected profit, conditional on the order flow. According to Vives (1995b), this condition can be justified by Bertrand competition among risk neutral MMs who observe the limit order book and have symmetric information. It can also be explained by a situation where liquidity traders submit market orders $z$ jointly with competitive, price taking privately informed speculators who submit optimal demand schedules $x$ and a continuum of risk neutral MMs who submit demand schedules based on prices to a central mechanism according to the semi-strong efficiency rule of Equation (8). Equilibrium prices are thereby set by a Walsarian centralized auctioneer (CA) (see also Yuan (2005), Ozsoylev and Werner (2011), and Pasquariello (2014)) to equate the aggregate excess demand from all the model’s market participants to zero. In this case, in equilibrium, Equation (8) is necessarily verified, since otherwise MMs would likely take unbounded positions.

From Equation (5), this implies that the optimal demand schedule $x_{LA}^*$ depends on risk aversion, loss aversion, market clearing price and the magnitude of the private signal. For a given private signal at a given equilibrium price, speculators optimal demand falls either within the no-trade interval or the trading interval. Thus, MMs have to guess speculators’ trading status. Following Pasquariello (2014) and in the spirit of Yuan (2005) we can express the inference problem as

\(^{19}\) A similar condition is found, for instance, in Kyle (1985), Hirshleifer et al. (1994), Vives (1995a, b), and Pasquariello (2014).
\[ P = E \left[ v \mid \omega, s \geq \frac{P}{\rho^2} + \Delta \right] \Pr \left[ s \geq \frac{P}{\rho^2} + \Delta \mid \omega \right] + E \left[ v \mid \omega, s \leq \frac{P}{\rho^2} - \Delta \right] \Pr \left[ s \leq \frac{P}{\rho^2} - \Delta \mid \omega \right] + E \left[ v \mid \omega, s - \Delta \leq \frac{P}{\rho^2} \right] \Pr \left[ s - \Delta \leq \frac{P}{\rho^2} \mid \omega \right], \]  

(9)

where \( \Pr \left[ s \leq \frac{P}{\rho^2} - \Delta \right] \), \( \Pr \left[ s \geq \frac{P}{\rho^2} + \Delta \right] \) are the probability of the order flow being informative, while \( \Pr \left[ s - \Delta \leq \frac{P}{\rho^2} \right] \) is the probability of the order flow giving no information about the risky payoff \( v \).

Since the optimal demand schedule \( x_{LA}^* \) of Equation (5) makes \( \omega \) a linear function of \( P \) and of the private signal \( s \) and since the boundaries are not functions of the received private signal \( s \) (i.e. \( \Delta \) does not depend on \( s \)), the inference problem of Equation (9) is analytically tractable, which leads to the following proposition

**PROPOSITION 2.** In the economy described above, with loss averse speculators endowed with private information, the equilibrium price function of the model is the fixed point of the implicit function given by

\[
P_{LA} = \frac{\gamma \sigma_v^2 \sigma_e^2}{\sigma_v^2 + \sigma_e^2 (1 + \gamma^2 \sigma_v^2 \sigma_e^2) \left( \frac{s}{\gamma \sigma_v^2} + z \right)} \left[ 1 - \Phi \left( \frac{P_{LA} + \Delta}{\rho^2} \frac{1}{\sqrt{\sigma_v^2 + \sigma_e^2}} \right) + \Phi \left( \frac{P_{LA} - \Delta}{\rho^2} \frac{1}{\sqrt{\sigma_v^2 + \sigma_e^2}} \right) \right] + \sigma_e \rho \left[ 1 - \frac{\gamma^2 \sigma_v^2 \sigma_e^4}{\sigma_v^2 + \sigma_e^2 (1 + \gamma^2 \sigma_v^2 \sigma_e^2)} \right] \psi \left( \frac{P_{LA} - \Delta}{\rho^2} \frac{1}{\sqrt{\sigma_v^2 + \sigma_e^2}} \right) - \psi \left( \frac{P_{LA} + \Delta}{\rho^2} \frac{1}{\sqrt{\sigma_v^2 + \sigma_e^2}} \right) \]

(10)

where \( \psi(x) \) refers to the probability density function of the standard normal distribution.

**PROOF.** See the appendix. □

If speculators do not exhibit loss aversion (i.e. \( \lambda = 1 \)), the rational equilibrium price function of Equation (10) is reduced to equilibrium price when speculators have CARA preferences

\[
P_{\text{CARA}} = \frac{\gamma \sigma_v^2 \sigma_e^2}{\sigma_v^2 + \sigma_e^2 (1 + \gamma^2 \sigma_v^2 \sigma_e^2) \left( \frac{s}{\gamma \sigma_v^2} + z \right)},
\]

(11)
Equation (11) is identical to the mean variance preferences, equilibrium price found by Pasquariello (2014) and, in particular, is a special case of the linear equilibrium in (Vives 2010, Proposition 1.11) when a continuum of risk averse speculators receive identical noisy signals of the asset payoff.

In equilibrium, informed agent $i$, buys or sells according to whether $s$, the private estimate of $v$ is larger than $\frac{P}{\rho^2} + \Delta$ or smaller than $\frac{P}{\rho^2} - \Delta$, and does not trade otherwise. In their trading region, informed agents trade more intensively if risk aversion ($\gamma$) is lower, and if the precision of the signal $\left(1/\sigma^2\right)$ is higher. Moreover, in our model, the precision of the signal $\left(1/\sigma^2\right)$ also shortens the no-trade region $(2\Delta)$, while $\gamma$ has no impact on determining that region. As in the CARA model, trading intensity is independent of the amount of noise trading.

Trade occurs in this type of model because of the presence of noise traders and because of the information advantage held by informed agents over the MMs. The asymmetric information between speculators and MMs creates typically two opposite effects, selection and information (efficiency). While higher-quality private signals encourage informed agents to trade more aggressively, and thus to exploit their information premium more efficiently, they also typically reveal more private information to the MMs. The insider’s information advantage still holds, but it could diminish or increase depending on risk aversion, the quality of private signal and the noise. In that sense, the camouflage concealing informed agents’ trading from MMs varies with the economy’s parameters. In our model, a third effect, related to the MMs’ uncertainty regarding the informed investors’ trading region, influences the information discovery process. Because of loss aversion, when the magnitude of the aggregate order flow is very low (high), MMs can be relatively sure (unsure) that the informed traders did not submit any limit order, inferring that the information advantage held by insiders is not (is) exploited (Equation (5)). In case of informative aggregate order flow, the trading intensity $\zeta$ outside the no-trade region is similar to that of the CARA model, and
therefore both the information content of the equilibrium price and the price itself should be close to that given by the CARA model.\textsuperscript{20}

To highlight the effect of loss aversion on information sharing and on the equilibrium price formation process, we numerically analysed an economy with a typical market-specific calibration, whose parameters make the expected return on the risky asset to 6\% and the standard deviation 20\%. We follow Hirshleifer et al.’s (1994) setting $\gamma = 2.5$, $\sigma_z^2 = 8$, $\sigma_z^2 = 1$.\textsuperscript{21} Fig. 3 illustrates an example of equilibrium price $P_{\text{LA}}(\Theta)$ as a function of $\Theta = \frac{s}{\gamma \sigma_z^2} + z$.\textsuperscript{22}

Fig. 3. Equilibrium Price

Note: The dashed line, the solid line, and the dash-dotted line represent equilibrium prices for risk averse speculators and loss averse speculators with a coefficient of loss aversion of 2.5 and 4 respectively.

\begin{itemize}
  \item \textsuperscript{20} Our non-linear model can generate multiple equilibria in the intermediate price region, but strong movement may occur without the presence of it, just because of the market maker confusion on speculators trading status.
  \item \textsuperscript{21} The value of the risk aversion coefficient is consistent with historical estimates of the market risk premium. We retrieve similar inferences from other market specification calibrations proposed in the literature (see, e.g., Gennette and Leland 1990; Leland 1992; and Yuan 2005).
  \item \textsuperscript{22} $\Theta$ refers to the statistically relevant part of the informative aggregate order flow observed by the MMs.
\end{itemize}
The equilibrium price is a non-linear function of the noisy demand and of the private signal intensity, while for the CARA model, $P_{\text{CARA}}(\Theta)$ is linear in $\Theta$. This non-linearity arises because of the uncertainty regarding informed investor trading status. In the two extreme regions (when $|\Theta|$ is high), there is very little uncertainty regarding informed trader status, and thus the price is equal to the linear price function of the CARA-Model. However, when $\Theta$ is around zero, MMs consider that most probably informed investors will not trade. In the intermediate region, a small movement in $\Theta$ can create large asset price movements.

The unique interaction between speculators’ loss aversion and MMs’ adverse selection can generate steep price movements, up or down. Fig. 4 graphs the sensitivity of the equilibrium price to signal and noise trading shocks for an economy populated by loss-averse informed traders endowed with private information.

**Fig. 4. Price Sensitivity to Signal and Supply Shocks**

![Graph](image)

Note: The lines in the left-hand graph represent equilibrium price as a function of the signal shock when the supply shock is -20, -8, 20, and 8. The lines in the right-hand graph represent equilibrium price as a function of supply shock when the signal shock is -50, 0, 80, and 400.

The equilibrium price becomes sensitive to shocks in the intermediate price region when it is more difficult for the MMs to infer the quality of the private signal and to conjecture the trading status of informed traders. The magnitude of such sensitivity decreases with the degree of precision of the private signal and increases
with the level of speculators’ loss aversion. In this model, large market downturns or upturns may occur following insignificant supply or informational shocks, regardless of the value of the underlying asset. Our model is consistent with empirical findings, reported by Cutler et al. (1989), that important price movements can occur without any particular news event.

### 2.2.1 Market Liquidity

The market liquidity measure $\lambda_{LA}^{-1}$ can be expressed as the inverse of the price impact $\lambda_{LA} = \frac{\partial P_{LA}}{\partial z}$. By implicit function theorem, the equilibrium price impact is

$$\lambda_{LA} = \frac{A[1 - \Phi(H) + \Phi(L)]}{1 + \frac{A}{\sigma_z \rho} \left( \frac{s}{\gamma \sigma_z^2} + z \right) \left( \psi(H) - \psi(L) \right) + \left( 1 - \sqrt{B} \right) \left( L \psi(L) - H \psi(H) \right)},$$

where $A = \frac{\gamma \sigma_v^2 \sigma_z^2}{\sigma_v^2 + \sigma_z^2 \left( 1 + \gamma \sigma_v^2 \sigma_z^2 \right)}$, $B = \frac{\gamma \sigma_v^2 \sigma_z^4}{\sigma_v^2 + \sigma_z^2 \left( 1 + \gamma \sigma_v^2 \sigma_z^2 \right)}$, $H = \frac{P}{\rho^2} + \Delta$, and $L = \frac{P}{\rho^2} - \Delta$. For $\lambda = 1$, the price impact is reduced to the equilibrium price impact of a risk averse speculator with constant absolute risk aversion $\lambda_{CARA} = A$. As stated above, the equilibrium price in our model is a non-linear function of both signal intensity and the noise trader demand $z$. Thus, the price impact is not constant. However, in the extreme region of the equilibrium price, the price impact $\lambda_{LA}$ of the implicit function is equal to the price impact in the presence of CARA speculator

$$\lim_{P \to \infty} \lambda_{LA} = A = \lambda_{CARA}.$$  

For a sufficiently large value of $P$, the relation between equilibrium market liquidity and all the parameters of the model (excepting loss aversion) is indeed the same as in the case of risk averse informed traders.

For the intermediate price region, the market depth is highly nonlinear in noise trading demand. As for the CARA normal case, the price impact is nonnegative, since the market maker attempts to offset losses due to the presumably adverse selection of the speculator with profits from noise trading. Fig. 5 illustrates
a numerical example of price impact for a given signal shock, with the specific calibration of the technology parameters discussed above, and for different degrees of loss aversion.

**Fig. 5. Price Impact**

Note: The graph represents the price impact (inverse measure of liquidity) of noise traders’ shocks where the private signal shock is 0, and for risk averse speculators and loss averse speculators with loss-aversion coefficients of 2.5 and 4 respectively.

We can separate the price impact into three distinct states corresponding to three different levels of inferred likelihood of informed trading status for MMs. A price impact close to zero minimizes MMs’ adverse selection problem. However, when the price impact is constant, the problem is merely that of mean variance. Finally, in between these extremes, the market depth emphasizes how difficult it is for MMs to infer the trading status, and thus a small supply shock can have a great effect on the equilibrium price initially unjustified while MMs misinterpret the trading status of the informed trader. Indeed, MMs cannot distinguish between a shock in the private signal and a shock in the noisy demand. Our model supports recent empirical evidence suggesting that the relationship between orders and price adjustment may be nonlinear where large price fluctuations occur when the market depth is low, in line with the comparative
static analysis we presented. This is consistent with the empirical study by Pástor and Stambaugh (2003) Pastor and Stambaugh (2003), which used a related measure of price sensitivities as a measure of market liquidity. The authors found several episodes of extremely low aggregate liquidity, including the October 1987 crash and the LTCM crisis of September 1998.

3. Asymmetric Price Movements

In section 2, we demonstrated how asymmetric information in the presence of loss averse informed traders creates large price movements in financial markets. In addition, we showed that large price changes might occur without any particularly dramatic news events. Yet this section fails to support the other main empirical evidence in the literature on market crashes; namely, the fact that large price movements are more likely to be decreases than increases.

Several models of asymmetric information introduce short-sale constraints while providing partial support for episodes where stock prices fall substantially. When crashes appear because of an increase (rather than a sudden fall) in confusion and uncertainty, the models of Barlevy and Veronesi (2003), Bai et al. (2005) and Marin and Olivier (2008) all require at least a fraction of traders to be unable to sell assets short, to explain the markets’ pervasive tendency to melt down. In an entirely different setting, Hong and Stein (2003) develop a disagreement (differences of opinion) model with no asymmetric information, which successfully predicts the three distinct features of market crashes. Interestingly, in their competing behavioral theory of crashes, they also introduce short-sale constraints in their model. We follow the same line of thought and extend our model to study the impact of short-sale constraints on optimal demand and equilibrium price. In this section, we derive the necessary conditions for the technology parameters. The unique interaction between asymmetric information, loss aversion and short-sale constraints supports the empirical evidence for large price movements tending to be downward rather than upward.

23 In practice, however, crashes appear to involve an increase in uncertainty. The empirical part of Marin and Olivier’s (2008) work indeed strongly supports this fact, showing that informed traders tend to leave the market before crashes.

24 Differences of opinion are associated with one of the two principal aspects of overconfidence, the better than average effect, since in their model each group of traders believes his signal is of better quality than that of the other group.
3.1 Equilibrium with Short-Sale Constraints

We consider a market identical to that in section 2. Furthermore, we assume that informed traders might be subject to short-sale constraints. Short-sale constraints mean that investor \(i\)'s position is bounded below by a non-positive number: \(x_i \geq -b_i\) where \(b_i \geq 0\). We assume that \(0 \leq \kappa < 1\) of informed traders are subject to short-sale constraints,\(^{25}\) and index them by \(i \in [0, \kappa)\), and that the rest, with mass \((1 - \kappa)\), are unconstrained. For convenience, the short-sale constraint is assumed to be the same for all constrained speculators, so we drop the subscript \(i\) associated with constraint \(b\). One can extend the development for the optimal demand of unconstrained speculators to show that the optimal demand schedules for constrained informed traders are \(\max \{x_{LA}^c, -b\}\), where \(x_{LA}^c\) refers to the optimal demand of Equation (5). Following our previous development, this result is straightforward, and given by the following.

**Proposition 3.** In the economy described above, the optimal demand for the loss averse and short-sale constrained informed trader is given by

\[
x_{LA}^c = \begin{cases} 
\dfrac{\rho^2 s - P}{\gamma \sigma_i^2 (1 - \rho^2)} - \dfrac{\Lambda(\lambda)}{\gamma \sigma_i \sqrt{1 - \rho^2}} & \text{for } s > \dfrac{P}{\rho^2} + \Delta \\
0 & \text{elsewhere} \\
\dfrac{\rho^2 s - P}{\gamma \sigma_i^2 (1 - \rho^2)} + \dfrac{\Lambda(\lambda)}{\gamma \sigma_i \sqrt{1 - \rho^2}} & \text{for } \dfrac{P - b \gamma \sigma_i^2 (1 - \rho^2)}{\rho^2} - \Delta < s \leq \dfrac{P}{\rho^2} - \Delta 
\end{cases}
\]

where \(\Delta = \dfrac{\Lambda(\lambda) \sigma_i \sqrt{1 - \rho^2}}{\rho^2}\), and \(\Lambda = \Lambda(\lambda)\) solves \(\Lambda(1 + (\lambda - 1)\Phi(-\Lambda)) - \dfrac{(\lambda - 1)}{\sqrt{2\pi}} e^{-\frac{1}{2}\Lambda^2} = 0\). Notice that we retain \(b\) as any non-negative number and do not set it as zero. We maintain the general case where \(b \neq 0\) since the interaction between loss aversion and short-sale constraint is sensitive to the choice of the parameter \(b\). For \(b = \infty\), Equation (14) is reduced to Equation (5).

---

\(^{25}\) Short-sale constraints are due to various market restrictions, such as the proportion of institutional trading in the market, cost of lenders, and regulatory restrictions.
The equilibrium price results from the presence of both unconstrained and constrained informed traders. We denote the aggregate order flow by \( \omega = \kappa x^c + (1 - \kappa) x^sc + z \), which refers to the noisy limit-order book schedule observed by market makers, where \( x^sc \) is given by Equation (5) and \( x^c \) refers to Equation (14).

MMs earn zero expected profit, conditional on the order flow. The market-clearing price \( P \) satisfies the semi-strong market efficiency rule expressed by Equation (8). Aggregating order flows from both unconstrained and constrained informed traders, the decision rule becomes

\[
P = E \left[ v \omega, s \geq \frac{P}{\rho^2} + \Delta \right] \Pr \left[ s \geq \frac{P}{\rho^2} + \Delta \right] + E \left[ v \omega, |s - \Delta| \leq \frac{P}{\rho^2} \right] \Pr \left[ |s - \Delta| \leq \frac{P}{\rho^2} | \omega \right],
\]

\[
+ E \left[ v \omega, \frac{P}{\rho^2} - \Gamma \leq s \leq \frac{P}{\rho^2} - \Delta \right] \Pr \left[ s \leq \frac{P}{\rho^2} - \Delta | \omega \right]
\]

\[
+ E \left[ v \omega, s \leq \frac{P}{\rho^2} - \Gamma \right] \Pr \left[ s \leq \frac{P}{\rho^2} - \Gamma | \omega \right]
\]

(15)

where \( \Gamma(\lambda, \sigma, \sigma_z, b) = \frac{\Lambda(\lambda) \sigma \sqrt{(1 - \rho^2)^3 + b \gamma \sigma^2 (1 - \rho^2)}}{\rho^2} \). For \( b = 0 \), \( \Gamma = \Delta \), and for \( b = \infty \), \( \Gamma = \infty \), and the decision rule is reduced to Equation (9). Similarly to previous results with unconstrained speculators only, \( \Pr \left[ |s - \Delta| \leq \frac{P}{\rho^2} \right] \) is the probability that the order flow will not provide information about the risky payoff \( v \), and \( \Pr \left[ s \leq \frac{P}{\rho^2} - \Delta \right], \Pr \left[ s \geq \frac{P}{\rho^2} + \Delta \right] \) are the probability of the order flow being informative. However, the amount of information provided differs within the different states. When \( s \geq \frac{P}{\rho^2} + \Delta \), the order flow is fully informative, since the short-sale constraints never bind. For \( s \leq \frac{P}{\rho^2} - \Delta \), the amount of information depends on the constraint level \( b \). The tractability remains because both unconstrained and constrained optimal demand schedules of Equation (5) and (14) make \( \omega \) a linear function of the private signal \( s \), and since the boundaries are not functions of the received private signal (e.g., \( \Delta \) and \( \Gamma \) do not depend \( s \)). Since the inference problem uses the same mathematical properties and follows very similar steps to those
described in appendix, we skip the intermediary steps. As the equilibrium price is quite cumbersome and lengthy, we report it in the appendix.

### 3.2 Skewness

Once we derive the equilibrium price function in an economy where some speculators have short-sale constraints, we can find the conditions for asymmetric price movements. Similarly to Barlevy and Verosini (2003) and Yuan (2005), but unlike Bai et al. (2005) and Marin and Olivier (2008) we present a model where short-sale constraints bind for high prices as reported in Equation (A.16) of the appendix.\(^\text{26}\) As reported earlier, in the unconstrained economy, market depth is constant for sufficiently high prices in absolute value. This remains the case in a constrained economy. However, the depth is no longer the same for high and low prices.

Downward movements will be more pronounced that upward movements if, and only if,

\[
\lim_{P \to -\infty} \lambda_{LA}^{SS} > \lim_{P \to +\infty} \lambda_{LA}^{S}, \quad \text{where} \quad \lambda_{LA}^{S} = \frac{\partial P_{LA}^{S}}{\partial z}. \quad \text{(This is equivalent, for a sufficiently large absolute value of the equilibrium price, to the following condition)\(^{27}\)}
\]

\[
\left\{ \gamma > \frac{\sqrt{\sigma_z^2 + \sigma_v^2}}{\sigma_z^2 \sigma_z} \right\} \quad \text{or} \quad \left\{ \gamma < \frac{\sqrt{\sigma_z^2 + \sigma_v^2}}{\sigma_z^2 \sigma_z} \quad \text{and} \quad \frac{\sigma_z^2 + \sigma_v^2 - \gamma^2 \sigma_z^2 \sigma_v^2}{\sigma_z^2 + \sigma_v^2} < \kappa < 1 \right\}. \quad (16)
\]

Besides the fact that high prices are less informative than low prices, since in the high-price regime, short-sale constraints bind, speculators trade less aggressively overall, revealing less information to the market makers, the selection effect and efficiency effect still play an important role in a constrained economy, particularly in determining the sign of the skewness of the risky asset. For a sufficiently large coefficient of risk aversion compared with other technology parameters of the economy, or for an economy with a short-selling ban, or at least an economy with a high level of short-sale restrictions (Equation (16)),

\(^{26}\) It is straightforward to demonstrate that the equilibrium price with short-sale constraints (Equation (A.16)) is reduced to the equilibrium price without short-sale constraints (Equation (10)) for sufficiently low value of \(P\), i.e.

\[
\lim_{P \to -\infty} P_{LA} = P_{LA-SS}.
\]

\(^{27}\) This condition is obtained when solving \(\lim_{P \to -\infty} \lambda_{LA}^{SS} > \lim_{P \to +\infty} \lambda_{LA}^{S}\) for \(\kappa\).
we observe an asymmetry of large price movements supporting the empirical evidence of negative market skewness. This indeed confirms the economic intuition; i.e. a positive shock moves the price above the fundamentals, and uninformed investor are more likely to be short-sale constrained. Hence, market makers are less willing to accommodate noise selling and thus dampen the upward price movements. However, our model might also generate positive skewness. Although under more restrictive conditions, this arises when the efficiency effect dominates the selection effect \( \gamma < \frac{\sigma_x^2 + \sigma_z^2}{\sigma_x^2 \sigma_z^2} \), and when the slight information disadvantage (asymmetry) between the high-price and low-price regimes that uninformed traders face cannot be compensated because of the insufficient number of constrained speculators
\[
\left( \kappa < \frac{\sigma_x^2 + \sigma_z^2 - \gamma^2 \sigma_x^2 \sigma_z^2}{\sigma_x^2 + \sigma_z^2} \right)
\]
that fail to exploit their private information.\(^{28}\) Therefore, in that situation, when constraints bind, the efficiency effect still prevails over the selection effect, but less than for a low equilibrium price. Therefore, \( \lim_{\lambda_{LA} \to -\infty} \lambda_{LA}^{SS} < \lim_{\lambda_{LA} \to +\infty} \lambda_{LA}^{SS} \).

This result indeed departs from the out-of-sample predictions of Yuan’s (2005) model. Her result indeed, unambiguously supports large asymmetric price falls. Markets are differently organized; uniformed traders and informed traders share the same preferences, and information is revealed through the self-fulfilling equilibrium price, rather than through the aggregate order flow, as in the present model. Risk neutrality in uninformed traders indeed changes the interplay between the so-called selection and efficiency effect and does not always lead to negative skewness. If we allow in Yuan’s (2005) setting uninformed traders to have different risk aversion, and particularly to be risk neutral, (unbiased efficient pricing rule) as in our model, MMs would like to take unbounded positions. This is also the reason why to justify efficient pricing rule we need to assume sequential trading coupled with competition among risk-neutral market makers with symmetric information, observing the limit order book (Vives (1995b)).\(^{29}\)

---

\(^{28}\) This is due to a decrease in expected trading volume of informed traders when constraints bind.

\(^{29}\) Since in Yuan (2005) fictitious economy without uniformed traders is used to solve the equilibrium (Blackwell Theorem) (DeGroot, 1986), we might assume that it isn’t the difference in risk aversion that leads to the asymmetry.
Although, as in Barlevy and Veronesi (2003) and Yuan (2005), crashes can occur even when the fundamental are strong, and the magnitude of the crashes depends on the number of unsophisticated passive investors present in the market, crashes also depend on uncertainty with regard to asset payoff and risk aversion. In the above conditions, the less uncertain the asset payoff, the more pronounced negative skewness, suggesting that skewness and price volatility are positively correlated.

Fig. 6 graphs the sensitivity of equilibrium price to signal and noise trading shocks.

**Fig. 6. Equilibrium Price with Short-Sale Constraints**

![Graph showing equilibrium price sensitivity to signal and noise trading shocks.]

Note: This graph represents equilibrium price as a function of the signal shock when the noise traders’ intensity is zero.

The multiplier effect of short-sale constraints, information asymmetry, and loss aversion is clearly visible in Fig. 6. In our model, the unique interaction between loss aversion of the speculator, adverse selection of price movements. Moreover, unreported development shows that if we replace in the proposed model, loss aversion coupled with short sale constraints with borrowing constraint (when assuming that $0 \leq k < 1$ of informed traders are subject to borrowing constraints) we would get asymptotically opposite conditions for the asymmetry between upward and downward movements.
between the informed traders and the MMs, and the presence of short-sale constraints among a fraction of speculators can produce a market crisis.30

In Fig. 7, a kernel estimation of the price distribution for a short-sale constrained economy with loss-averse speculators has fatter tails than the standard model with unconstrained speculators and CARA–preferences predicts and is negatively skewed. This indeed highlights the asymmetry between market meltdown and upward market price movement. Large price drops are more severe than upward movements. Equilibrium price becomes sensitive to shocks in the intermediate price region, when it is more difficult for the market maker to infer the quality of the private signal and to make conjectures about the trading status of informed traders.

Fig. 7. Kernel Estimation of the Equilibrium Price Distribution

Note: The dashed line represents the kernel distribution of the equilibrium price distribution based on 200 draws of \( (s,z) \) in an economy with loss aversion, asymmetric information, and short-sale constraints. The solid line represents the kernel estimation and the graph represents equilibrium distribution for an economy with asymmetric information only.

---

30 As in Yuan (2005), we define a market crisis as a large price drop in response to a small shock to the economic environment.
The magnitude of such sensitivity decreases with the private signal’s degree of precision and increases with the level of speculators’ loss aversion. Notice that asymmetry increases with the number of constrained informed traders and the level of constraint $b$. Short-sale constraints interact with loss aversion at a very fundamental level. One speculator may not trade because of either loss aversion, short-sale constraint, or these two factors combined. The more speculators are constrained, the more difficult it is for MMs to infer a positive signal from the insider.

4. Contagion

The pattern of co-movement across apparently uncorrelated assets is not easy to explain. Financial crises often spill over to unrelated markets or to markets with little economic linkage. We extend our model to multiple, independent, and uncorrelated risky assets, and test whether it sheds light on the third important stylized fact about market crashes, namely, the fact that an idiosyncratic shock unique to one market affects asset prices in uncorrelated markets. In this section, we attempt to show that in a multiple-risky-assets economy, price movements can occur even without any shock to its fundamentals. A small informational or supply shock in a single uncorrelated asset of one speculator’s portfolio might suddenly induce MMs to update their opinion about the trading status of informed traders and therefore to revise the reservation price of more than one risky asset. Therefore, the price of one asset can be affected by a shock to another independent and uncorrelated asset through this specific uninformed traders’ uncertainty channel, induced by speculators’ loss aversion. We refer to this spillover mechanism as the contagion effect.

To illustrate this effect, we consider the same two-date economy as defined in section 2 but with $N$ risky assets instead of one. While taking the risk-free asset to be the numeraire, we let $P_j$ be the price for the risky asset $j$. Prior to trading, each informed investor receives the same $N$ private signals $(s_1, s_2, ..., s_N)$, related to the payoff of each risky asset. We assume the distribution of every final asset payoff, noisy demand, and private signal $(v_j, z_j, \varepsilon_j, \forall j \in N)$ are IID; i.e. that the private signals are independent realizations and that $\text{cov}(v_i, v_j) = 0$, $\text{cov}(z_i, z_j) = 0$, and $\text{cov}(\varepsilon_i, \varepsilon_j) = 0$, for all $i \neq j \in N$. 
4.1 Linkage of Optimal Demands Due to Loss Aversion

Let $x_j(s_j,\ldots)$ represent the demand schedule for the risky asset $j$ of an informed trader given private signal $s_j$. When the price realization is $P_j$, the demand function is then $x_j(s_j, P_j)$. Speculator $i$ decides on the optimal holding for each security $x_j \forall j = 1,\ldots,N$, maximizing $E[-\exp(-\gamma \pi) | s_1, s_2, \ldots, s_N]$, where gains and losses are derived at the portfolio level $\pi = \sum_{j=1}^{N} x_j(v_i - P_i)$. Extending the development of section 2 for one risky asset to multiple risky assets, we find that there is a one-to-one correspondence between each pair of assets’ optimal demand

$$x^*_k = \frac{x^*_m \sigma_m (P_k - s_k \rho^2_m) (1 - \rho^2_m)}{\sigma_k (P_m - s_m \rho^2_m) (1 - \rho^2_k)} \quad \text{for } \forall k \neq m \in N,$$

and we obtain the following proposition\footnote{We use 1 to denote indicator functions.}

PROPOSITION 4. In an uncorrelated multiple-risky-asset economy, loss averse informed traders either trade for all the risky assets or do not trade at all, and the optimal demand for the risky asset $j$ is given by

$$x^*_j = \frac{\rho^2_j s_j - P_j}{\gamma \sigma_j^2 (1 - \rho^2_j)} \left[ 1 - \frac{\Lambda(\lambda)}{r} \right] \mathbb{1}\{r \geq \Lambda(\lambda)\}$$

(18)

where $r^2 = \sum_{k=1}^{N} \frac{(s_k - P_k / \rho^2_k)^2}{\sigma_k^2 (1 - \rho^2_k)}$.

The implicit Equation $\frac{r^2}{\Lambda^2(\lambda)} = 1$ represents a $N$-dimensional ellipsoid in the signal space $(s_1, s_2, \ldots, s_N)$ with ellipsoid-axis radii $(\frac{\Lambda(\lambda) \sigma_1}{\rho^2_1 \sqrt{1 - \rho^2_1}}, \frac{\Lambda(\lambda) \sigma_2}{\rho^2_2 \sqrt{1 - \rho^2_2}}, \ldots, \frac{\Lambda(\lambda) \sigma_N}{\rho^2_N \sqrt{1 - \rho^2_N}})$, and center $(\frac{P_1}{\rho^2_1}, \frac{P_2}{\rho^2_2}, \ldots, \frac{P_N}{\rho^2_N})$, delimiting the no-trade region. From Equation (18), one can observe that if the intensity of the
multidimensional private signal is too weak and lies inside the ellipsoid, speculators will not trade at all, given their informational advantage. For $N = 1$, Equation (18) reduces to Equation (5).

Interestingly, from Equation (17) we see that speculators do not trade for a subset of risky assets only. The trading region applies uniformly to all assets. Either informed traders submit their demand schedules for all assets simultaneously, or they remain silent and do not seek to trade in any risky asset. This might seem counterintuitive at first, but one can observe that if a private signal on a single asset is much stronger than those on the remaining assets, speculators would certainly trade aggressively in that asset (Equation (18)), independently of the low signal quality of the remaining assets, traded at an inversely proportional intensity (Equation (17)). From a geometric viewpoint, one strong $I$-dimension signal (coordinate) that departs from the origin $(\frac{P_1}{\rho_1}, \frac{P_2}{\rho_2}, ..., \frac{P_N}{\rho_N})$, along its axis, guarantees that the private information vector $(s_1, s_2, ..., s_N)$, lies outside the ellipsoid. Therefore, having very accurate information on a subset of securities is enough for all risky securities to be traded by the informed traders. Portfolio-level loss aversion may enable speculators to exploit weak information that would not have been exploited in a single-risky-asset economy. Strong information advantage in certain markets, which decreases the likelihood of a global loss event for loss-averse speculators, might indeed be used as an insurance on investments in the other markets. Conversely, for a moderate value of $r$ and $r \leq \Lambda(\lambda) \ (r > \Lambda(\lambda))$, a small information shock on one market might push the entire signal vector inside (outside) the trading region, therefore preventing (permitting) speculators from suddenly trading in other markets.

4.2 Contagion in a Two-Risky-Asset Economy

Similar to the one-risky-asset economy, MMs infer the private information from the aggregate order flow for each security $j = 1, ..., N$. Following the semi-strong market efficiency rule, the equilibrium price is $P(\omega_j) = E[v_j|\omega_j]$ where $\omega_j = x_j^* + z_j$ represents the aggregate order flow for asset market $j$. To
illustrate the spillover effect, let restrict our economy to \( N = 2 \).\(^{32}\) MMs inference problem in a two-risky-asset is therefore

\[
\begin{align*}
P_1 &= E\left[v_1 \mid \omega_1(s_1, s_2, P_1, P_2, z_1), r \geq \Lambda(\lambda) \right] \Pr\left[ r \geq \Lambda(\lambda) \right] + E\left[v_1 \mid z_1, r \leq \Lambda(\lambda) \right] \Pr\left[ r \leq \Lambda(\lambda) \right] \\
P_2 &= E\left[v_2 \mid \omega_2(s_1, s_2, P_1, P_2, z_2), r \geq \Lambda(\lambda) \right] \Pr\left[ r \geq \Lambda(\lambda) \right] + E\left[v_2 \mid z_2, r \leq \Lambda(\lambda) \right] \Pr\left[ r \leq \Lambda(\lambda) \right]
\end{align*}
\]

(19)

where \( \omega_1(s_1, s_2, P_1, P_2, z_1) = \frac{\rho_1^2 s_1 - P_1}{\gamma \sigma_1^2 (1 - \rho_1^2)} + z_1 \) and \( \omega_2(s_1, s_2, P_1, P_2, z_1) = \frac{\rho_2^2 s_2 - P_2}{\gamma \sigma_2^2 (1 - \rho_2^2)} + z_2 \) refer to the informative order flow when speculators submit non-zero orders. Non linearity of the informative order in the two-market prices \( P_1 \) and \( P_2 \) and private signals \( s_1 \) and \( s_2 \) as well as the non centered nature of the conditional elliptical region \( \left\{ (s_1, s_2) \in \frac{r^2}{\Lambda^2(\lambda)} = 1 \right\} \) make the conditional moments in Equation (19) analytically intractable.\(^{33}\) All the probabilities of Equation (19) can be found analytically. It is easy to show that in a two-risky-asset economy \( r \) follows a rice distribution \( r \sim \text{Rice}(\nu, 1) \) with non-centrality parameter

\[ \nu = \sqrt{\sum_{k=1}^{2} \left( \frac{P_k}{\sigma_k \sqrt{1 - \rho_k^2}} \right)^2}. \]

\(^{34}\) We employ a numerical approach to express

\[ E\left[v_j \mid \omega_j(s_1, s_2, P_1, P_2, z_1), r \geq \Lambda(\lambda) \right] \quad \text{and} \quad E\left[v_j \mid z_j, r \leq \Lambda(\lambda) \right] \]

as explicit functions of \( \omega_j \) and \( P_j \) for \( j = 1, 2 \); estimated via ordinary least Square (OLS).\(^{35}\) We describe the approach in the appendix, which yields to the following proposition

\(^{32}\) The basic contagion result holds for more general cases of \( N > 2 \). We decide to illustrate the mechanism with two uncorrelated markets for the sake of clarity.

\(^{33}\) Note however that recently Arismendi and Broda (2017) derive analytical solution for the unconditional elliptical truncated moments. For conditional truncation, closed formed expression has not been developed yet.

\(^{34}\) While the Marcum-Q function can be used to represent the cumulative distribution function

\[ \Pr\left[ r \leq \Lambda(\lambda) \right] = 1 - Q \left( \sum_{k=1}^{2} \left( \frac{P_k}{\sigma_k \sqrt{1 - \rho_k^2}} \right)^2, r \right) \]

to be able to solve numerically the implicit functions of the equilibrium prices, we use non-central Wilson-Hilferty approximation (Abdel-Aty, 1954) to approximate the probability of the order flow being informative or not.

\(^{35}\) To approximate non-linear equilibrium, we assume that MMs estimate conditional expectation from the best linear predictors of \( v_j \), \( j = 1, 2 \); (Hayashi, 2000) for each market in the same spirit of Pasquariello (2014) for a single-risky-asset economy.
PROPPOSITION 5. In an uncorrelated two-risky-asset economy with loss averse informed traders, equilibrium price functions \( P_1 \) and \( P_2 \) are the solutions of the following implicit functions

\[
P_1 = \left( \hat{a}_{1H} + \hat{b}_{1H} \left( \frac{\rho^2 s_1 - P_1}{\gamma \sigma_n^2 (1 - \rho^2)} \right) \left[ 1 - \frac{\Lambda(\lambda)}{r(P_1, P_2)} \right] + \hat{c}_{1H} P_1 \right) + \left( 1 - \Phi \left( \frac{\alpha(P_1, P_2) - 1 - \beta(P_1, P_2)}{\delta(P_1, P_2)} \right) \right)
\]

\[
P_2 = \left( \hat{a}_{2H} + \hat{b}_{2H} \left( \frac{\rho^2 s_2 - P_2}{\gamma \sigma_n^2 (1 - \rho^2)} \right) \left[ 1 - \frac{\Lambda(\lambda)}{r(P_1, P_2)} \right] + \hat{c}_{2H} P_2 \right) + \left( 1 - \Phi \left( \frac{\alpha(P_1, P_2) - 1 - \beta(P_1, P_2)}{\delta(P_1, P_2)} \right) \right)
\]

where \( \alpha(P_1, P_2), \beta(P_1, P_2) \) and \( \delta(P_1, P_2) \) are defined in the appendix, and the exogenous parameters \( \hat{a}_{1H}, \hat{b}_{1H}, \hat{c}_{1H} \) and \( \hat{a}_{2H}, \hat{b}_{2H}, \hat{c}_{2H} \) and \( \hat{a}_{2L}, \hat{b}_{2L}, \hat{c}_{2L} \) are OLS coefficients in market 1(2) of the MMs approximating the conditional mean of \( v_1(v_2) \) for the informative and uninformative order flow \( \omega_1(s_1, s_2, P_1, P_2, z_1) \) \( \omega_2(s_1, s_2, P_1, P_2, z_2) \) and \( z_1(z_2) \) respectively.

Note that it is clear from Equations (19) and (20) that the equilibrium price of from one market is affected by idiosyncratic shocks from the other market.\(^{36}\) MMs inference behavior creates contagion across the two independent markets. Even when informed investors do not trade at all because of loss aversion, MMs incorporate the probability of informed trading into their inferences about the value of the underlying assets.

Fig. 8 graphs the sensitivity of the equilibrium prices to the private signal in both markets. The contagion occurs in the intermediate price regions. Since in that regions MMs are confused on the trading status of informed traders, forcing them to adjust equilibrium prices abruptly. This time however, the cause of an abrupt adjustment on one market might be a change in the fundamentals of an uncorrelated market. Because MMs know the speculators’ decision process, they might suddenly realize that the aggregate order flow has

\(^{36}\) MMs’ inference problem for \( P_1(P_2) \) is a function of \( P_2(P_1) \).
just become uninformative because of the homogeneous conditions of the state-dependent optimal demand schedule (Equation (18)) for every risky asset.

**Fig. 8. Equilibrium Prices in a Two-risky-Asset Economy**

Note: The dashed line and the starred line reflect the equilibrium prices in market 1 and 2 as functions of signal shocks \( s_2 \) (when \( s_1 = 0 \)) and \( s_1 \) (when \( s_2 = 0 \)) respectively, i.e. the contagion effect. The solid line and the squared line represent equilibrium prices as functions of signal shocks from the same market, for loss averse speculators with a coefficient of loss aversion of 2.5 and zero supply shocks.

The source of multiple equilibria in our model is due to the confusion of the MMs on trading status because of speculators’ loss aversion. In two-risky asset risky economy this confusion becomes even more pronounced because of the possibility for the traders to be confused from multiple sources (two signal spaces). Multiple equilibria are becoming more trivial.\(^{37}\)

\(^{37}\) Extensive simulations show also that the elliptical region affects substantially the stability of the equilibrium. While the main implication of our model on contagion is robust to alternative calibrations of the technology parameters, the stability of the equilibrium varies nonetheless with the technology parameters. We allow therefore the private signals and supply shocks to be more precise and report the comparative statics for \( \sigma_c^2 = 1, \sigma_e^2 = 1 \) for both markets.
Finally, it is important to note that one limitation to our model is that the contagion effect is symmetrical. To address the empirical evidence that the spillover effect is often larger during market downturn, than during market upturn,\textsuperscript{38} we should introduce short-sale constraints in our multiple-risky-asset setting. However, when introducing short sale constraints the elliptical trading region does not apply uniformly to all assets, making the derivation of the equilibrium unpractical.\textsuperscript{39}

5. Concluding Remarks

The study of market crashes has traditionally attracted a great deal of attention both in academia and among practitioners. The proposed theory illustrates the consequences of speculators’ loss aversion on the formation of market crashes.

The equilibrium clarifies the role loss aversion plays on market makers’ inference problem. Loss aversion restrains speculators from trading for weak signals. Therefore, when the aggregate order flow is low, market makers are very confused, and have difficulty to infer properly the speculators’ trading status, so both the equilibrium price and the market depth become highly non-linear. In that situation, a small adverse shock to the fundamentals can trigger a large movement in asset value.

When introducing short-sale constraints, the model provides asymmetry between upward and downward price movements, in line with empirical evidence. For a large set of technology parameters, downward price movements are indeed likely to be more severe than equivalent upward price movements. The proposed model also provides new testable implications for the nature of crashes. Asset returns are likely to exhibit more positive skewness in markets where short-sale constraints are less binding. Finally, we demonstrate that in a multiple-risky-asset economy, contagion can occur even between uncorrelated risky assets. Our model’s predictions match historical evidence of market crashes.

\textsuperscript{38} See e.g., Ang and Chen, (2002) and Boyer et al., (2006). Recently, the result of Ahmed and Huo (2019) mitigates this evidence. They show that during the Chinese stock market crash of 2015 price spillovers from China to other regional markets were more significant during a bullish period.

\textsuperscript{39} When introducing short-sale constraints in multiple asset setting, we are not able to derive analytically the optimal demand, which makes the derivation of the equilibrium unpractical.
Policymakers can always benefit from studying the impact of cognitive psychology on the price formation process. From a regulatory perspective, the presence of short-sale constrained, better-informed, loss-averse traders mitigates the effectiveness of bans or restrictions on short sales, often defended by regulators during market stress.

We also believe that the tractability of the equilibrium presents a starting point for further research to investigate the role of asymmetric information with more realistic preferences. For example, examining the impact of private information on insurance and hedging under loss aversion might explain the welfare consequences of improvements in private information release from a behavioral economics perspective. It would also be interesting to isolate the role of insiders, because insider trades might have some power to predict market crashes. Making informed trades observable by all market participants would make it possible to distinguish between the impact of insiders and more general forms of informed traders. Our intuition is that such a model would stress even further the role of insiders in predicting market crashes.

Appendix

Derivation of Equation (2)

The utility function can be written as

\[ U(\pi, \gamma, \lambda) = -\frac{1}{\gamma} e^{-\pi} + \frac{(\lambda-1)}{\gamma} (1-e^{-\pi}) 1\{\pi < 0\}. \] (A.1)

The conditional expectation is therefore given by

\[ E[U(\pi, \gamma, \lambda) | s] = -\frac{1}{\gamma} E[e^{-\pi} | s] + \frac{(\lambda-1)}{\gamma} (1-E[e^{-\pi} | s, \pi < 0]) Pr(\pi < 0 | s), \] (A.2)

Note also that depending on positive or negative demand schedule \((x)\) the terms of Equation (A.1), conditional on losses, \(\pi < 0\) i.e. \(x(\check{v} - P) < 0\), will yield to different integrals. For positive value of \(x\),

\[ Marin and Olivier (2008) develop a model highlighting the “dogs that did not bark” effect where uninformed investors react more strongly to the absence of insider sales than to their presence. This effect is responsible in their model for abrupt price movements. We plan to follow their recommendation for the possible extension of their model where some form of irrationality prevails. \]
\( \pi < 0 \) refers to \( \bar{v} < \bar{P} \) and for negative value of \( x \), \( \pi < 0 \) refers to \( \bar{v} > \bar{P} \). Each integral terms of Equation (A.1) can be easily computed in closed forms:

\[
E\left[ e^{-\pi}\right] = e^{-\gamma(\mu_{v} - \bar{P})x + \frac{\gamma^{2}v^{2}\sigma_{v}^{2}}{2}},
\]

(A.3)

\[
\Pr\left( \pi < 0 | s \right) = \Phi\left( \text{sgn}(x) \frac{\mu_{v/s} - P}{\sigma_{v/s}} \right),
\]

(A.4)

and

\[
E\left[ e^{-\pi} | s, \pi < 0 \right] = \frac{e^{-\gamma(\mu_{v} - \bar{P})x + \frac{\gamma^{2}v^{2}\sigma_{v}^{2}}{2}} \Phi\left( \text{sgn}(x) \frac{\mu_{v/s} - x\gamma\sigma_{v/s}^{2} - P}{\sigma_{v/s}} \right)}{\Phi\left( \text{sgn}(x) \frac{\mu_{v/s} - P}{\sigma_{v/s}} \right)}.
\]

(A.5)

Plugging (A.3), (A.4), and (A.5), into (A.2) yields to Equation (2).

**Proof of Proposition 1**

Define (4) as \( \zeta(\Lambda, \lambda) = 0 \) where we denote \( \zeta_{+}(\Lambda, \lambda) = 0 \), for \( x \geq 0 \), and \( \zeta_{-}(\Lambda, \lambda) = 0 \) for \( x < 0 \). Since \( \lim_{\Lambda \to \infty} \zeta(\Lambda, \lambda) = \infty \), \( \lim_{\Lambda \to -\infty} \zeta(\Lambda, \lambda) = -\infty \), and for any \( \lambda \geq 1 \), \( \zeta(\Lambda, \lambda) \) is a strictly increasing function in \( \Lambda \) i.e., \( \frac{\partial \zeta}{\partial \Lambda} = 1 + (\lambda - 1) \Phi(\Lambda) > 0 \) and \( \frac{\partial \zeta}{\partial \Lambda} = 1 + (\lambda - 1) \Phi(-\Lambda) > 0 \), the solution \( \Lambda^{*} \) of (4) exists and it is unique, for any degree of loss aversion (\( \lambda \geq 1 \)). □

**Proof of Proposition 2**

Each conditional expectation and probability of Equation (9) is tractable in our setting. We can express the conditional moments of the truncated normal variables in closed-form (Maddala 1986). Since \( z \) and \( v \) are independent, for the no-trade region

\[
E\left[ v | \omega = z_{s} - \Delta \leq \frac{P}{\rho^{2}} \right] = \rho \sigma_{v} \psi \left( \frac{P}{\rho^{2}} - \Delta \right) - \psi \left( \frac{P}{\rho^{2}} + \Delta \right),
\]

(A.6)

\[
\Phi \left( \frac{P}{\rho^{2}} - \frac{\Delta}{\sqrt{\sigma_{v}^{2} + \sigma_{\omega}^{2}}} \right) - \Phi \left( \frac{P}{\rho^{2}} + \frac{\Delta}{\sqrt{\sigma_{v}^{2} + \sigma_{\omega}^{2}}} \right).
\]
whereas, for the informed trading region,

\[
E \left[ v \mid \omega_1 = \frac{\rho^2 s - P}{\gamma \sigma_v^2 (1 - \rho^2)} + \frac{\Lambda(\lambda)}{\gamma \sigma_v \sqrt{1 - \rho^2}} + z, s \leq \frac{P}{\rho^2} - \Delta \right] = \mu_{v/\omega_1} - \frac{\rho \sigma_{v/\omega_1} \psi \left( \frac{P}{\rho^2} - \Delta \right)}{\sqrt{\sigma_v^2 + \sigma_z^2}},
\]

(A.7)

and

\[
E \left[ v \mid \omega_2 = \frac{\rho^2 s - P}{\gamma \sigma_v^2 (1 - \rho^2)} - \frac{\Lambda(\lambda)}{\gamma \sigma_v \sqrt{1 - \rho^2}} + z, s \geq \frac{P}{\rho^2} + \Delta \right] = \mu_{v/\omega_2} + \frac{\rho \sigma_{v/\omega_2} \psi \left( \frac{P}{\rho^2} + \Delta \right)}{\sqrt{\sigma_v^2 + \sigma_z^2}},
\]

(A.8)

where \( \rho^* \) refers to the correlation coefficient of the conditional bivariate normal variable \( v, s \mid \omega \). The conditional expectation and standard deviation of normally distributed variables (Greene 2003, pp. 90) are

\[
\mu_{v/\omega} = \frac{\text{cov}(v, \omega)}{\text{var}(\omega)}(\omega - E[\omega]), \quad \sigma_{v/\omega} = \sigma_v \left( 1 - \frac{E[v|\omega]}{\sigma_v \sigma_\omega} \right), \quad \text{where} \quad w - E(\omega) = \frac{s}{\gamma \sigma_z} + z, \quad \text{cov}(v, \omega) = \frac{\sigma_v^2}{\gamma \sigma_z},
\]

and \( \text{var}(\omega) = \frac{1}{\gamma^2 \sigma_z^2} + \frac{\sigma_v^2}{\gamma^2 \sigma_z^4} + \sigma_z^2 \). These conditional moments are equal for the lower and upper region

\[
\omega_1 = \frac{\rho^2 s - P}{\gamma \sigma_v^2 (1 - \rho^2)} + \frac{\Lambda(\lambda)}{\gamma \sigma_v \sqrt{1 - \rho^2}} + z, \quad \omega_2 = \frac{\rho^2 s - P}{\gamma \sigma_v^2 (1 - \rho^2)} - \frac{\Lambda(\lambda)}{\gamma \sigma_v \sqrt{1 - \rho^2}} + z;
\]

\[
\mu_{v/\omega_1} = \mu_{v/\omega_2} = \mu_{v/\omega} = \frac{\gamma \sigma_v \sigma_z^2}{\gamma^2 \sigma_z^2 (1 + \gamma^2 \sigma_z^2)} \left( \frac{s}{\gamma \sigma_z^2} + z \right),
\]

(A.9)

\[
\sigma_{v/\omega_1} = \sigma_{v/\omega_2} = \sigma_{v/\omega} = \frac{\sqrt{\gamma^2 \sigma_z^2 (1 + \gamma^2 \sigma_z^2)}}{\gamma^2 \sigma_z^2 (1 + \gamma^2 \sigma_z^2)}.
\]

(A.10)
Using well-known properties of conditional multivariate normal distribution (Rencher 2002, pp. 88), the variance covariance matrix and correlation coefficient bivariate normal variable v,s|ω are

\[
\Sigma^* = \begin{bmatrix}
\sigma_v^2 \sigma_s^2 (1 + \sigma_v^2 \gamma^2 \sigma_s^2) & \gamma^2 \sigma_v^2 \sigma_s^2 \\
\sigma_v^2 + \sigma_s^2 (1 + \sigma_v^2 \gamma^2 \sigma_s^2) & \sigma_v^2 + \sigma_s^2 (1 + \sigma_v^2 \gamma^2 \sigma_s^2) \\
\gamma^2 \sigma_v^4 \sigma_s^2 & \gamma^2 \sigma_v^4 (\sigma_v^2 + \sigma_s^2) \\
\sigma_v^2 + \sigma_s^2 (1 + \sigma_v^2 \gamma^2 \sigma_s^2) & \sigma_v^2 + \sigma_s^2 (1 + \sigma_v^2 \gamma^2 \sigma_s^2)
\end{bmatrix}
\]  
(A.11)

where \(\Sigma^*\) is the same for \(\omega_1\) as well as for \(\omega_2\). From \(\Sigma^*\), we find that

\[
\rho^* = \frac{\rho \gamma \sigma_v \sigma_s}{\sqrt{1 + \gamma^2 \sigma_s^2 \sigma_v^2}}.
\]  
(A.12)

The probabilities of Equation (9) are given by

\[
\Pr\left[ s - \Delta \leq \frac{P}{\rho^2} \right] = \Phi \left( \frac{P - \Delta}{\rho^2 \sigma_v^2 + \sigma_s^2} \right) - \Phi \left( \frac{P}{\rho^2 \sigma_v^2 + \sigma_s^2} \right); \quad \Pr\left[ s \leq \frac{P - \Delta}{\rho^2} \right] = \Phi \left( \frac{P - \Delta}{\rho^2 \sigma_v^2 + \sigma_s^2} \right);
\]

\[
\Pr\left[ s > \frac{P}{\rho^2} + \Delta \right] = 1 - \Phi \left( \frac{P}{\rho^2 \sigma_v^2 + \sigma_s^2} + \Delta \right).
\]

The equilibrium price of Equation (10) is then obtained by replacing Equations (A.9), (A.10), and (A.11) into Equations (A.6), (A.7), (A.8), and Equations (A.6), (A.7), and (A.8) and (A.13) into Equation (9). Given \(g(P) = f(P) - P\), where \(f(P)\) is the right side of Equation (10), and since \(\lim_{x \to -\infty} \Phi(x) = 0\), \(\lim_{x \to -\infty} \Phi(x) = 1\), and \(\lim_{x \to -\infty} \psi(x) = 0\), it is immediately clear that \(\lim_{P \to -\infty} g(P) < 0\), and \(\lim_{P \to -\infty} g(P) > 0\). According to the Intermediate Value Theorem, at least one solution to \(g(P)\) exists \(\Box\)

**Equilibrium price with short-sale constraints and loss aversion**

Using the same relations as for the unconstrained economy, we can separately develop all the terms of Equation (15). The main difference is in the aggregation of two different types of traders, unconstrained and constrained. The first two terms are not subject to any constraints. The aggregate order flow of the first
and third terms reflects the participation of all traders; the second term implies the participation of noise traders only, while the last term implies the participation of both noise traders and unconstrained informed traders. Therefore, the development is similar as in the unconstrained economy except for the last term. Short-sale constraints are binding. It is therefore necessary to compute a new untruncated conditional expectation and standard deviation:

\[
\mu_{v/s} = \frac{\gamma \sigma_v^2 \sigma_z^2 (1 - \kappa)}{(1 - \kappa)^2 (\sigma_v^2 + \sigma_z^2) + \gamma^2 \sigma_z^4 \sigma_z^2} \left( \frac{(1 - \kappa) s}{\gamma \sigma_z^2} + z \right)
\]

(A.14)

\[
\sigma_{v/s} = \sqrt{\frac{\sigma_v^2 \sigma_z^2 (1 - \kappa)^2 + \sigma_z^2 \gamma^2 \sigma_z^2}{(\sigma_v^2 + \sigma_z^2) (1 - \kappa)^2 + \gamma^2 \sigma_z^4 \sigma_z^2}}.
\]

(A.15)

The correlation coefficient of the bivariate normal variable \(v, s|\omega\) of the first and third term of Equation (15) is given in (A.12). For the second term, it is simply \(\rho\), and therefore, for the fourth term, \(\rho^* = \frac{\rho \sigma_v \sigma_z}{\sqrt{(1 - \kappa)^2 + \gamma^2 \sigma_z^2 \sigma_z^2}}\). Having all the parameters of the conditional truncated normal distribution of each of the four terms of Equation (15), the price function for the equilibrium price can be expressed as the following fixed-point problem.
\begin{align*}
P_{LA}^u &= \frac{\gamma \sigma_v^2 \sigma_e^2}{\sigma_v^2 + \sigma_e^2 (1 + \gamma \rho_e^2 \sigma_e^2)} \left( s + \frac{P_{LA}^u - \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) + \Phi \left( \frac{P_{LA}^u + \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) - \Phi \left( \frac{P_{LA}^u - \Gamma}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) \\
&\quad + \frac{\gamma \sigma_v^2 \sigma_e^2 (1 - \kappa)}{(1 - \kappa)^2 (\sigma_v^2 + \sigma_e^2) + \gamma \rho_e^2 \sigma_e^2} \left( (1 - \kappa) s + \frac{P_{LA}^u - \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) \Phi \left( \frac{P_{LA}^u + \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) - \Phi \left( \frac{P_{LA}^u - \Gamma}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) \\
&\quad + \sigma_P \sqrt{\frac{\gamma \rho_e^2 \sigma_e^2}{\sigma_v^2 + \sigma_e^2 (1 + \gamma \rho_e^2 \sigma_e^2)}} \left[ \psi \left( \frac{P_{LA}^u + \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) + \psi \left( \frac{P_{LA}^u - \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) - \psi \left( \frac{P_{LA}^u - \Gamma}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) \right] \\
&\quad - \sigma_P \sqrt{\frac{\gamma \rho_e^2 \sigma_e^2}{\sigma_v^2 + \sigma_e^2 (1 - \kappa)^2 + \gamma \rho_e^2 \sigma_e^2}} \left[ \psi \left( \frac{P_{LA}^u - \Gamma}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) + \sigma_P \psi \left( \frac{P_{LA}^u + \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) - \sigma_P \psi \left( \frac{P_{LA}^u - \Delta}{\rho_P^2 / \sigma_e^2 + \sigma_e^2} \right) \right] \\
&= (A.16)
\end{align*}

**Numerical approach: derivation for the two-risky-asset equilibrium**

MMs Inference problem in equation (19) required the computation of the first moments for both the informative and the uninformative order flows. Since both cannot be computed analytically, we compute these moments as explicit functions of \( \omega_j \) and \( P_j \) for \( j = 1,2 \); We assume that MMs are simulating a large number of the realization of the economy and estimate a linear relation between \( v \) and \( \omega_j \) and \( P_j \); as MMs would do analytically in case of CARA normal setting for uncorrelated assets (see Equation (11)).

We specify first two prices grids: \( P_1(n) \) made of \( N \) points between \( P_{1L} \) and \( P_{1H} \), and \( P_2(n) \) made of \( N \) points between \( P_{2L} \) and \( P_{2H} \);\(^{41}\) where for \( j = 1,2 \); \( P_{jL} \) (\( P_{jH} \)) are the equilibrium with CARA normal preferences with \( v_j = \frac{-3\sigma_v}{3\sigma_v} \) and noise trading and signal error for each market are equal to their unconditional mean \( z_j = 0 \), and \( \epsilon_j = 0 \).

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\(^{41}\) We choose \( N = 2000 \). The method is robust to different choices of grids.
Then, we simulate $M$ realizations of the private signals $s_j(m) = v_j(m) + \varepsilon_j(m)$ and noise trading $z_j(m)$, when $v_j(m)$, $z_j(m)$, and $\varepsilon_j(m)$ are set from their unconditional normal distribution.

For each realization of the private signals, $s_j(m)$ and prices $P_j(n)$, we compute the matrix

$$R(m,n) = \frac{(s_1(m) - P_1(n)/\rho_1^2)^2}{\sigma_1^2(1 - \rho_1^2)} + \frac{(s_2(m) - P_2(n)/\rho_2^2)^2}{\sigma_2^2(1 - \rho_2^2)}.$$ 

We then assign vectors $P_{Hj}(n) = P_j(n)$ ($P_{Hj}(n) = P_j(n)$) and $s_{Hj}(m) = s_j(m)$ ($s_{Hj}(m) = s_j(m)$) for private signals and prices that satisfy the condition $R(m,n) \geq \Lambda(\lambda) \left( R(m,n) \leq \Lambda(\lambda) \right)$.

The informative order flow is then defined as

$$\omega_{Hj}(m,n) = \rho_j^2 s_{Hj}(m) - P_{Hj}(n) \left[ 1 - \frac{\Lambda(\lambda)}{R(P_{Hj}(n),P_{Hj}(n))} \right]$$

$+ z_j(m)$ and the uninformative order flow is $\omega_{Uj}(m) = z_j(m)$.

Since any random variable can be expressed as $y = E[y|x] + \varepsilon$ (Greene, 2003). To represent the conditional moments we employ the following linear regression:

$$v_{Hj}(m) = a_{Hj} + b_{Hj} \omega(m,n) + c_{Hj} P_j(n) + \varepsilon(m,n) \quad \text{for } j = 1,2 \quad (A.17)$$

$$v_{Uj}(m) = a_{Uj} + b_{Uj} \omega(m,n) + c_{Uj} P_j(n) + \varepsilon(m,n) \quad \text{for } j = 1,2 \quad (A.18)$$

Estimation using OLS leads to

$$E[\hat{v}_j | \omega_j, r \geq \Lambda(\lambda)] \approx \hat{a}_{Hj} + \hat{b}_{Hj} \omega_j + \hat{c}_{Hj} P_j \quad \text{for } j = 1,2 \quad (A.19)$$

$$E[\hat{v}_j | \omega_j, r \leq \Lambda(\lambda)] \approx \hat{a}_{Uj} + \hat{b}_{Uj} \omega_j + \hat{c}_{Uj} P_j \quad \text{for } j = 1,2 \quad (A.20)$$
Finally, the coefficients to approximate the probabilities \( \Pr[r \leq \Lambda(\lambda)] = 1 - \Phi\left( \frac{\alpha - 1 - \beta}{\delta} \right) \) and

\[
\Pr[r \geq \Lambda(\lambda)] = \Phi\left( \frac{\alpha - 1 - \beta}{\delta} \right)
\]

are

\[
\alpha = \frac{\sum_{k=1}^{2} \left( s_k - P_k / \rho_k^2 \right)^2}{2 + \sum_{k=1}^{2} \left( \frac{P_k}{\sigma_{v_k} \sqrt{1 - \rho_k^2}} \right)^2}^{1/3}
\]

\[
\beta = \frac{2 \left( k + 2 \sum_{k=1}^{2} \left( \frac{P_k}{\sigma_{v_k} \sqrt{1 - \rho_k^2}} \right)^2 \right)}{9 \left( k + 2 \sum_{k=1}^{2} \left( \frac{P_k}{\sigma_{v_k} \sqrt{1 - \rho_k^2}} \right)^2 \right)^2}
\]

and \( \delta = \frac{\sqrt{2 \left( k + 2 \sum_{k=1}^{2} \left( \frac{P_k}{\sigma_{v_k} \sqrt{1 - \rho_k^2}} \right)^2 \right)^2}}{9 \left( k + 2 \sum_{k=1}^{2} \left( \frac{P_k}{\sigma_{v_k} \sqrt{1 - \rho_k^2}} \right)^2 \right)^2} \).

Substituting \( \omega_1 = \frac{\rho^2_1 s_1 - P_1}{\gamma \sigma^2_{v_1} (1 - \rho^2_1)} + z_1 \) and \( \omega_2 = \frac{\rho^2_2 s_2 - P_2}{\gamma \sigma^2_{v_2} (1 - \rho^2_2)} + z_2 \)

into Equations (A.19), (A.20), the equilibrium prices of Equation (20) is thus obtained by replacing Equations (A.19), (A.20), and the probabilities of informative and uninformative order flows above into Equation (20).

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