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PRICE, TRADE SIZE, AND INFORMATION IN SECURITIES MARKETS*

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This paper investigates the effect of trade size on security prices. We show that trade size introduces an adverse selection problem into security trading because, given that they wish to trade, informed traders perfer to trade larger amounts at any given price. As a result, market makers' pricing strategies must also depend on trade size, with large trades being made at less favorable prices. Our model provides one explanation for the price effect of block trades and demonstrates that both the size and the sequence of trades matter in determining the price-trade size relationship.

1. Introduction

In an efficient market, the price of a security should reflect the value of its underlying assets. Yet, empirically, we observe that large trades (known as blocks) are made at 'worse' prices than small trades. Further, these block trades have persistent price effects, with transaction prices lower after block sales and higher after block buys. If markets are efficient, why does trade size or quantity affect security prices?

One explanation is that the inventory imbalance resulting from a block transaction forces security prices to change. Because large trades force market makers away from their preferred inventory positions, prices for these transactions must compensate specialists for bearing this inventory risk [see Stoll (1979), Ho and Stoll (1981), and O'Hara and Oldfield (1986)]. This inventory or 'liquidity effect' hypothesis suggests that how much prices change with trade size depends on the absolute size of the trade and on the market maker's inventory position before the trade.

In this paper, we develop an alternative explanation for the price–quantity relationship. We show that quantity matters because it is correlated with

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private information about a security's true value. In particular, we show that an adverse selection problem arises because, given that they wish to trade, informed traders prefer to trade larger amounts at any given price. Since uninformed traders do not share this quantity bias, the larger the trade size, the more likely it is that the market maker is trading with an informed trader. This information effect dictates that the market maker's optimal pricing strategy also depends on quantity, with large trade prices reflecting this increased probability of information-based trading. In our model, trade size affects security prices because it changes perceptions of the value of the underlying asset.

That information could affect security prices is an idea researched by numerous authors. Although there is a voluminous literature in the rational expectations area [see Jordan and Radner (1982)], our work is more closely related to papers by Bagehot (1971), Copeland and Galai (1983), and Glosten and Milgrom (1985). Those authors demonstrate that the possibility of information-based trading can induce a spread between bid and ask prices. This spread compensates the market maker for the risk of doing business with traders who have superior information. Our inclusion of quantity in security trading extends this research in several important ways. We show that the possibility of information-based trading need not always result in a bid–ask spread. Depending on market conditions, such as width (the ratio of large to small trade size) or depth (the fraction of large trades made by the uninformed), informed traders may choose to trade only large quantities, leaving the price for small trades unaffected. Even if the informed choose to trade both large and small quantities, however, our work demonstrates that prices and spreads will differ across quantities, with large trades being made at less favorable prices.

Our work also identifies a second important effect of information on the price–quantity relationship. Although the market maker faces uncertainty about whether any individual trader is informed, there is also uncertainty about whether any new information even exists. This latter uncertainty dictates that both the size and the sequence of trades matter in determining the price–quantity relationship. We show that these two information effects can explain the distinctive price path of block trades. Whereas the first effect causes prices to worsen for a block trade, the second effect causes the partial price recovery that characterizes most block trading sequences. Our analysis suggests that information alone can explain the price behavior of block trades without appealing to inventory adjustment costs.

Whether the information-effect theory or the liquidity-effect theory provides more insight into stock price behavior remains, of course, an empirical question. By developing a formal model of the price–quantity–information link, however, our work provides testable hypotheses to differentiate between these two theories. For example, our model predicts that the entire sequence of trades, and not merely the aggregate volume, determines the relationship of prices to quantities. This sequence effect also implies that the stochastic process of security prices (or even of prices and trades) will not be a Markov process. These results should be of interest to researchers in examining transaction-price data.

2. Price, quantity, and trading

We consider a model in which potential buyers and sellers trade assets with dealers (market makers). Each market maker sets prices at which he will buy or sell any quantity of the traded asset. Because we are interested in the effect of information on these prices, we assume that there are at least two risk-neutral market makers.[1] The multiplicity of dealers results in competitive asset pricing; their risk neutrality removes the influence of risk preferences from these competitive prices. Initially, we analyze the first trade in a trading day. We then extend the analysis to consider the subsequent sequence of trades.

The value of the asset is represented by the random variable V. We define an information event as the occurrence of a signal, s, about V, where this signal can take one of two values, low and high. The probability that this signal is low (L) is δ, the probability that it is high (H) is $1-\delta$, and $0<\delta<1$. Let $\underline{V}=\mathrm{E}\{V|s=L]$ and $\overline{V}=\mathrm{E}[V|s=H]$ where $\overline{V}>\underline{V}$. We let α denote the probability of an information event occurring before the beginning of the trading day, $0<\alpha\leq 1$. We assume that an information event will eventually occur and that information events occur only between trading days.[2]

If an information event occurs, some fraction of the traders learn the value of the signal. We assume that the informed traders are risk-neutral. We also assume that the number of traders who become informed is large, so that each acts competitively. What matters for asset pricing is not the number (or fraction) of informed traders, but rather the fraction of trades that come from informed traders. This fraction differs if the trading intensity of informed traders differs from that of uninformed traders. Let the market makers'

[1] Our modeling of competing market makers is consistent with a wide range of institutional arrangements. The over-the-counter (OTC) market, for example, generally has competing market makers in a stock. Although the New York Stock Exchange (NYSE) has only one exchange specialist per stock, there is potential competition from several sources. Floor traders act as market makers and, hence, compete with the specialist. In addition, the Intermarket Trading System (ITS) linking the regional exchanges to the NYSE means that the NYSE specialist must compete against the quotes offered by the regional specialists. This potential competition can force even a monopolist to set zero-profit prices. In our model, therefore, the second dealer can be a potential, rather than an actual, participant. Phillips and Smith (1980) analyze the effects of this potential competition. For an analysis of different making arrangements, see O'Hara and Oldfield (1986).

[2] It is possible to allow information events to occur within a trading day. This complicates the analysis, but does not change the nature of the results.

expectation of the fraction of trades made by the informed following an information event be μ.[3]

The market makers and the uninformed traders do not know whether an information event has occurred, nor, of course, do they observe the signal. They do know, however, that an information event will eventually occur and they know the information structure. Thus, their initial unconditional expectation of the asset's value is $V^* = \delta \underline{V} + (1-\delta)\overline{V}$.

For trades to occur, potential buyers and sellers must have motivations for trading and for trading at various quantities. As Milgrom and Stokey (1982) demonstrate, these motivations cannot be strictly speculative. If trades were solely information-related, any uninformed trader would do better to leave the market rather than face a certain loss trading with an informed investor. To avoid this no-trade equilibrium, we assume that the uninformed trade (at least partially) for liquidity reasons. This exogenous demand arises either from an imbalance in the timing of consumption and income or from portfolio considerations. We allow this demand to differ across individuals.

A related issue concerns the quantity uninformed traders wish to buy or sell. If liquidity demands differ, some traders prefer to trade large quantities whereas others favor small amounts. If prices vary across quantities, however, these large traders are penalized by worse prices. In actual security markets, several factors encourage large traders to remain large. Transactions costs, for example, decline with quantity, so a trader facing large liquidity needs will prefer to trade one large quantity rather than several smaller ones. Risk aversion can also be important in the quantity decision. Since prices move over time, trading once at the known large-quantity price can dominate trading at uncertain, possibly falling, prices with a multiple-small-trade strategy.

To simplify the analysis, we do not explicitly incorporate either transactions costs or risk aversion into the model. Instead, we assume that, for whatever reason, uninformed traders desire to trade various quantities. For our purpose, two such quantities on each side of the market are sufficient, although the model can be extended to the many-quantities case. We assume that potential uninformed buyers desire to buy either (integer) quantity B^1 or B^2, with $0 < B^1 < B^2$; potential uninformed sellers desire to sell either (integer) quantity S^1 or S^2, with $0 < S^1 < S^2$. We let $X_S^i > 0$ and $X_B^i > 0$, $i = 1, 2$, be the fraction of uninformed traders who, if they arrive at a dealer, want to trade S^i and B^i, $i = 1, 2$.

[3] The polar case of $\mu = 1$ corresponds to assuming that, if an information event occurs, the informed make all of the trades. Provided $\alpha \neq 1$, market makers still face uncertainty about the extent of information-based trading, since they do not know when such events occur. A more likely scenario is that the informed make only some fraction of trades. This corresponds to μ taking an intermediate value, $0 < \mu < 1$.

In addition to the motivations of uninformed traders, we must consider the trading motivations of informed traders and market makers. Since the informed observe the signal about the asset's value, their trading motivations are straight-forward: they trade to maximize their expected profit. Market makers trade because there is some chance that they are dealing with an uninformed trader and, hence, are not always being taken advantage of by an informed trader.[4] As Bagehot (1971) notes, it is the profit made from uninformed traders, offsetting the loss to the informed traders, that makes the market exist. Dealers do not know a priori, however, whether any individual is informed, nor do they know if an information event has, in fact, occurred. A dealer must decide at what price to buy or sell any quantity, and in so doing must consider both traders' information and competitors' actions. To solve this decision problem, each market maker must calculate the probabilities of trading with an uninformed trader, a trader informed of a low signal, or a trader informed of a high signal, all conditional on the price–quantity offers he and his competitors make.

Having defined the structure of the market, we now need to describe how trades actually transpire. In our market, a trader, selected according to the probabilities above, arrives and asks the competing market makers for their price–quantity quotes. The trader then either does not trade, takes the best quote for the quantity he wants to trade if he is uninformed, or takes the profit-maximizing quote if he is informed. If the trader is indifferent between quotes, he selects a dealer at random.

Market makers compete in these markets through price–quantity quotes. Each dealer selects an expected profit-maximizing supply-and-demand schedule, given his competitors' supply-and-demand schedules. For specialist j, a strategy is $d^j(q)$, the price per unit dealer j will pay for q units, and $c^j(q)$, the price per unit he will charge for q units. Market makers play a game, in these strategies, against each other.

Several features of the dealers' problems deserve comment. First, whether dealers announce all, part, or none of their supply-and-demand schedules before traders arrive is irrelevant. Each market maker must decide what to do when asked for a quote; every other market maker, and every trader, can also solve this decision problem. Second, since dealers compete through supply-and-demand schedules, two competing agents are sufficient to create the competitive outcome [see Mas-Colell (1980)]. Finally, market makers maximize expected trading profit from the trade in question. A risk-neutral dealer adjusts for inventory if there is some carrying or borrowing cost; since we

[4]Specialists, of course, also receive trading commissions. These commissions give the specialist his reservation wage. Our analysis of zero profit on each trade is thus consistent with zero profit above this reservation level.

analyze only a short period, we ignore such costs. Thus, dealers do not adjust their quotes to take account of their inventory.

3. Equilibrium trading

At the beginning of the trading day, each market maker must determine his initial prices for trading specific quantities of the traded asset. In equilibrium, these price–quantity quotes must yield each market maker zero expected profit on each trade. If, instead, a market maker anticipated trades with positive expected profits, a competing market maker could offer a slightly better price, thereby capturing the market and raising his or her expected profit. This process stops only when expected profits are driven to zero for every possible trade.

Although there is a large number of potential price–quantity pairs, market makers need only determine prices for quantities that potential uninformed traders desire to trade. In our model, this means that prices need be calculated only for quantities B^1, B^2, S^1, and S^2.

In this market, only two forms of equilibria can occur. If informed traders trade only large quantities, they are separated from small uninformed investors. We call this a separating equilibrium.[5] Alternatively, if the informed, with positive probability, trade either small or large quantities, a pooling equilibrium occurs. In the remainder of this section we delineate the market conditions under which a separating or a pooling equilibrium exists. In section 4, we characterize and compare the two equilibria.

3.1. The separating equilibrium

We first consider a market in a separating equilibrium (we demonstrate later when this occurs). In this market, a trader arrives and desires to trade $Q_1 \in [B^1, B^2, S^1, S^2]$, where a subscript denotes the time of the trade $t = 1, 2, \ldots$ In determining initial (or $t = 1$) trading prices, market makers must consider the information content of each potential trade. That is, before any trades occur, each market maker believes $\Pr\{V = \underline{V}\} = \delta$. If an information event has occurred, then for some traders the expected value of the asset is higher (if $s = H$) or lower (if $s = L$) than the market makers' expectation V^*. This influences the informed traders' desired trading quantity, with good news causing traders to buy B^2 and bad news eliciting trades of S^2.

To determine the trading prices, therefore, each market maker must calculate the conditional value of δ given the type of trade. If no information event

[5] We use the term 'separating equilibrium' for semantic simplicity. Although the informed are separated from the small uninformed, they are not, of course, separated from all of the uninformed. This 'semi-separating' equilibrium differs from more standard separating equilibria in which total separation occurs.

has occurred, δ remains unchanged. Alternatively, if an information event has occurred, the true δ is one if the signal is low and zero if the signal is high. The market makers' updating formula is thus

$$\begin{aligned}\delta_1(Q_1) &= \Pr\{V=\underline{V}\,|\,Q_1\} \\ &= 1\cdot\Pr\{s=L\,|\,Q_1\} + 0\cdot\Pr\{s=H\,|\,Q_1\} \\ &\quad +\delta\cdot\Pr\{s=0\,|\,Q_1\},\end{aligned} \tag{1}$$

where $s=0$ denotes no information event. Calculation of the individual probabilities for each type of trade is mathematically tedious, so we outline the procedure. We assume that market makers are Bayesians, so the conditional probability for any information event with outcome x is given by

$$\Pr\{s=x\,|\,Q_1\} = \frac{\Pr\{s=x\}\Pr\{Q_1|s=x\}}{\begin{aligned}&\Pr\{s=L\}\Pr\{Q_1|s=L\}\\ &+\Pr\{s=H\}\Pr\{Q_1|s=H\}\\ &+\Pr\{s=0\}\Pr\{Q_1|s=0\}\end{aligned}}\,. \tag{2}$$

Market makers calculate (2) for each trading quantity to determine the appropriate δ_1 to use in setting initial trade prices.

It is easy to demonstrate that $\delta_1(B^1)=\delta_1(S^1)=\delta$. That is, the market makers' conditional expectation of δ, given a small trade, is the same as the unconditional expectation. Thus, if the market can be characterized by a separating equilibrium, market makers know that any informed trader will trade only large quantities, so small trades cannot be information-based. As a result, a small trade does not affect the probability a market maker attaches to $V=\underline{V}$. This is not the case with large trades. For a large sale, the conditional δ is

$$\delta_1(S^2) = \delta\frac{\alpha\mu + X_S^2[1-\alpha\mu]}{\alpha\mu\delta + X_S^2[1-\alpha\mu]} \geq \delta. \tag{3}$$

Because a large sale may be information-based, market makers increase the probability they attach to $V=\underline{V}$. As (3) demonstrates, this adjustment depends on the probability attached to an information event having occurred (α) and on the fraction of traders believed to be informed (μ). If there is no possibility of an information event or there are no trades by informed traders, then $\delta_1(S^2)=\delta$. In either case, a large trade can have no information content, so there is no need to adjust δ. It is easy to demonstrate that $\partial\delta_1(S^2)/\partial(\alpha\mu)>0$, or the greater the likelihood of such trading, the greater the adjustment in δ.

A similar, albeit opposite, revision occurs with a large buy,

$$\delta_1(B^2) = \delta \frac{X_B^2(1-\alpha\mu)}{\alpha\mu(1-\delta) + X_B^2(1-\alpha\mu)} \leq \delta, \tag{4}$$

with

$$\partial\delta_1(B^2)/\partial(\alpha\mu) < 0.$$

Given these conditional expectations, market makers can set their initial bid and ask prices for each trading quantity. As would be expected, the bid and ask prices for small quantities, b_1^{1*} and a_1^{1*}, must equal V^*. Because the zero-profit constraint requires a price for any quantity equal to the market makers' expectation of V given that quantity, this expectation is simply $\delta\underline{V} + (1-\delta)\overline{V} = V^*$. The equilibrium bid and ask prices for large quantities, b_1^{2*} and a_1^{2*}, differ from V^* to reflect the probability of trading with an informed trader. These prices are given by

$$b_1^{2*} = V^* - \frac{\sigma_v^2}{[\overline{V} - \underline{V}]}\left[\frac{\alpha\mu}{X_S^2(1-\alpha\mu) + \delta\alpha\mu}\right], \tag{5}$$

$$a_1^{2*} = V^* + \frac{\sigma_v^2}{[\overline{V} - \underline{V}]}\left[\frac{\alpha\mu}{X_B^2(1-\alpha\mu) + \alpha\mu(1-\delta)}\right], \tag{6}$$

where σ_v^2 is the prior variance of V.

Eqs. (5) and (6) demonstrate the effect of quantity on security prices. Because of the possibility that large trades are information-based, market makers' pricing strategies must incorporate this information–quantity link, with large trades transacting at worse prices. If no such information link exists (i.e., if $\alpha\mu = 0$), our model indicates that prices will not depend on quantity, and all trades will take place at V^*. The next section analyzes these pricing strategies in more detail.

These prices determine a separating equilibrium only if traders who become informed choose to trade large quantities. Since we assume that the number of traders who become informed in an information event is large, each trader will ignore the effect of his trades on future trading opportunities. This essentially assumes that the security market under asymmetric information functions as a competitive market. In a competitive security market, each informed trader maximizes his expected profits trade by trade. So, for a trader informed of $s = L$, we will have a separating equilibrium if expected profit is no lower trading S_2 than trading S_1, or

$$S^2[b_1^{2*} - \underline{V}] \geq S^1[b_1^{1*} - \underline{V}]. \tag{7}$$

Substituting for b_1^{1*} and b_1^{2*} yields the necessary condition

$$S^2/S^1 \geq 1 + \alpha\mu\delta/X_S^2(1-\alpha\mu). \tag{8}$$

A similar necessary condition holds for a trader informed of $s = H$:

$$B^2/B^1 \geq 1 + \alpha\mu(1-\delta)/X_B^2(1-\alpha\mu). \tag{9}$$

Eqs. (8) and (9) dictate when the advantage of large quantity, or trade size, outweighs the better price available for a small trade.[6] If $\alpha\mu < 1$ and the market is wide enough (i.e., B_2 is large in relation to B_1 and S_2 in relation to S_1), informed traders trade only at B_2 and S_2, and a separating equilibrium exists. Similarly, if $\alpha\mu > 0$ and the market of large uninformed traders is shallow enough (i.e., X_S^2 and X_B^2 are small), a separating equilibrium will not exist.

These results are summarized in the following proposition. Let $c_1^*(q)$ and $d_1^*(q)$ be market makers' supply-and-demand schedules for the first trade, where

$$\begin{aligned} c_1^*(q) &= V^* && \text{if} \quad B^1 \geq q \geq 0, \\ &= a_1^{2*} && \text{if} \quad B^2 \geq q > B^1, \\ &= \overline{V} && \text{if} \quad q > B^2, \end{aligned}$$

and

$$\begin{aligned} d_1^*(q) &= V^* && \text{if} \quad S^1 \geq q \geq 0, \\ &= b_1^{2*} && \text{if} \quad S^2 \geq q > S^1, \\ &= \underline{V} && \text{if} \quad q > S^2. \end{aligned}$$

Proposition 1 [Separating equilibrium]. *There is an equilibrium with* $c_1^j(\cdot) = c_1^{j*}(\cdot)$, *for all dealers* j, *if and only if*

$$B^2/B^1 \geq 1 + \alpha\mu(1-\delta)/X_B^2(1-\alpha\mu).$$

There is an equilibrium with $d_1^j(\cdot) = d_1^{j*}(\cdot)$, *for all dealers* j, *if and only if*

$$S^2/S^1 \geq 1 + \alpha\mu\delta/X_S^2(1-\alpha\mu).$$

[6] The inclusion of transactions costs that decline with quantity also serves to make the separating equilibrium more likely to prevail. Such transactions costs give informed traders an additional incentive to purchase large, rather than small, quantities. Thus, it would be easier to separate them from small uninformed traders.

3.2. The pooling equilibrium

If Proposition 1's necessary conditions (8) and (9) are violated on either side of the market, then there can be no separating equilibrium on that side of the market. There will, however, be a pooling equilibrium. In a pooling equilibrium there is a positive probability of the informed trading in both large and small quantities. Let $\psi_1^B(\psi_1^S)$ be the probability that a trader informed of $s = H$ $(s = L)$ trades the smaller quantity $B^1(S^1)$. Let b_1^i be a typical dealer's bid price for the first trade of S^i. For $(\hat{b}_1^i, \hat{a}_1^i, \hat{\psi}_1^B, \hat{\psi}_1^S)$ to describe a pooling equilibrium, they must satisfy three conditions (the analysis for the ask side of the market is symmetric).

First, an informed trader must be indifferent between trading a large and a small quantity. A trader informed of $s = L$, for example, must anticipate an equal expected profit from trades of $(S^1, \hat{b}_1^1)$ and $(S^2, \hat{b}_1^2)$, and this requires $S^1[\hat{b}_1^1 - \underline{V}] = S^2[\hat{b}_1^2 - \underline{V}]$.

Second, market makers must anticipate zero expected profit from each trade. This requires $\hat{b}_1^1$ equal to V^* times the probability of trading S^1 with an uninformed trader plus $\underline{V}$ times the probability of trading S^1 with a trader informed of $s = L$. Simple calculations show

$$\hat{b}_1^1 = \hat{\delta}(S^1)\underline{V} + (1 - \hat{\delta}(S^1))\overline{V}, \tag{10}$$

where the conditional probability that $V = \underline{V}$, given a trade of S^1, is

$$\hat{\delta}(S^1) = \delta\left[\hat{\psi}_1^S\mu\alpha + (1 - \alpha\mu)X_S^1\right] / \left[\delta\alpha\hat{\psi}_1^S\mu + (1 - \alpha\mu)X_S^1\right].$$

The corresponding zero-profit condition for b_1^2 is

$$\hat{b}_1^2 = \hat{\delta}(S^2)\underline{V} + (1 - \hat{\delta}(S^2))\overline{V},$$

where

$$\hat{\delta}(S^2) = \delta\left[(1 - \hat{\psi}_1^S)\mu\alpha + (1 - \alpha\mu)X_S^2\right] / \left[\delta\alpha(1 - \hat{\psi}_1^S)\mu + (1 - \alpha\mu)X_S^2\right]. \tag{11}$$

Third, it must be possible to choose a $\hat{\psi}_1^S$ with $0 < \hat{\psi}_1^S \leq 1$ and simultaneously satisfy the equal-profit condition for any informed traders and the zero-profit condition for the dealers.[7] This requires

$$S_2/S_1 < 1 + \alpha\mu\delta/X_S^2(1 - \alpha\mu). \tag{12}$$

[7] As is typical of pooling models, the modeler chooses the level of ψ. That is, since informed traders are indifferent between trading small and large quantities in a pooling equilibrium, we assign $\hat{\psi}_1^S$ to S_1.

Hence, if $\alpha\mu > 0$ and the market is narrow enough (i.e., S_2 is close to S_1) or shallow enough (X_S^2 is small), a pooling equilibrium prevails. Since condition (12) is the reverse of the necessary condition for the separating equilibrium, there is always a separating or a pooling equilibrium on each side of the market.

These results and the symmetric results for ask prices are summarized in the following proposition. Let $\hat{c}_1(q)$ and $\hat{d}_1(q)$ be market makers' supply-and-demand schedules for the first trade, where

$$\begin{aligned}\hat{c}_1(q) &= \hat{a}_1^1 \quad \text{if} \quad B^1 \geq q \geq 0,\\ &= \hat{a}_1^2 \quad \text{if} \quad B^2 \geq q > B^1,\\ &= \overline{V} \quad \text{if} \quad q > B^2,\end{aligned}$$

and

$$\begin{aligned}\hat{d}_1(q) &= \hat{b}_1^1 \quad \text{if} \quad S^1 \geq q \geq 0,\\ &= \hat{b}_1^2 \quad \text{if} \quad S^2 \geq q > S^1,\\ &= \underline{V} \quad \text{if} \quad q > S^2.\end{aligned}$$

Proposition 2 [Pooling equilibrium]. *There is an equilibrium with* $c_1^j(\cdot) = \hat{c}_1(\cdot)$, *for all dealers j, if and only if*

$$B^2/B^1 < 1 + \alpha\mu(1-\delta)/X_B^2(1-\alpha\mu).$$

There is an equilibrium with $d_1^j(\cdot) = \hat{d}_1(\cdot)$, *for all dealers j, if and only if*

$$S^2/S^1 < 1 + \alpha\mu(1-\delta)/X_S^2(1-\alpha\mu).$$

4. Characterization of equilibrium prices and spreads

Propositions 1 and 2 reveal three major factors determining whether the market is in a separating or a pooling equilibrium. First, if $\alpha\mu < 1$, then in markets where large amounts can be traded in a single transaction (i.e., the large trade sizes B_2 and S_2 are large in relation to the small trade sizes B_1 and S_1) a separating equilibrium will prevail. If the big traders are big enough, they protect little traders from the adverse effect on price that results from being pooled with the informed. Second, in markets where large trades rarely occur (i.e., X_S^2 and X_B^2 are small), a pooling equilibrium will prevail. If there are few uninformed traders willing to trade large quantities, prices for large quantities will differ greatly from small-trade prices. This, in turn, makes it more profitable for informed traders to trade small rather than large quantities. Finally, in markets with a low probability of information-based trading (i.e., $\alpha\mu$ is low), a separating equilibrium will prevail. With either few trades made by informed traders or rarely occurring information events, prices for large quantities will be close to V^*, and the informed will choose to trade large quantities. These results are summarized below.

Proposition 3 [Equilibrium and market conditions, $0 < \alpha\mu < 1$]. *The market will be in a separating equilibrium if (1) the market has sufficient width or (2) there are few information-based trades.*

The market will be in a pooling equilibrium if (1) the market is sufficiently narrow or shallow or (2) there are many information-based trades.

Market conditions determine both prices in each equilibrium and which equilibrium prevails. In either equilibrium, if there is any chance that trades are information-based, large traders will buy at a price above and sell at a price below the small-trade price. But how much these prices diverge depends on market conditions.

Proposition 4. For a market in a separating equilibrium, with $0 < \alpha\mu < 1$, (1) there is a spread at large quantities but not at small quantities (i.e., $a_1^{2*} > a_1^{1*} = V^* = b_1^{1*} > b_1^{2*}$), (2) market width does not affect prices, (3) a_1^{2*} decreases and b_1^{2*} increases with increased depth, and (4) a_1^{2*} increases and b_1^{2*} decreases with increases in the probability of information-based trading.

Proposition 5. For a market in a pooling equilibrium, with $0 < \alpha\mu < 1$, (1) there is a spread at both large and small quantities (i.e., $\hat{a}_1^2 > \hat{a}_1^1 > V^* > \hat{b}_1^1 > \hat{b}_1^2$) and (2) market width affects prices, with $\hat{a}_1^2$ increasing and $\hat{a}_1^1$ decreasing with width and $\hat{b}_1^2$ decreasing and $\hat{b}_1^1$ increasing with width.

Propositions 4 and 5 summarize the effect of market conditions on security prices. One intriguing result is the different effect of width across the two equilibria. In a pooling equilibrium, increasing width reduces the probability that the informed trade small quantities, and this, in turn, affects prices. In a separating equilibrium, however, the informed already trade only large quantities, so increasing width cannot affect trading behavior, and thus cannot affect prices.

These propositions also indicate that there may be a spread between the prices at which market makers will buy or sell any quantity of the asset. This spread arises as compensation for the risk of trading with individuals who have superior information. That information problems could induce such a spread was also noted by Copeland and Galai (1983) and Glosten and Milgrom (1985). As we demonstrate, however, this spread need not be constant across quantities. For notational simplicity, let the spreads at small and large quantities be $T^1 = a^1 - b^1$ and $T^2 = a^2 - b^2$, with T^* and $\hat{T}$ distinguishing the spreads for separating and pooling equilibria.

Proposition 6 [Characterization of the spread]. *(1) If $\alpha\mu = 0$, there is no spread at either large or small quantities. (2) For any $\alpha\mu > 0$, the spread increases with trade size (i.e., $T^{2*} > T^{1*} = 0$ and $\hat{T}^2 > \hat{T}^1 > 0$). (3) The spread T^{2*}, $\hat{T}^1$, or $\hat{T}^2$ need not be symmetric around V^*. (4) For $1 > \alpha\mu > 0$, T^{2*} decreases with increased depth and with reductions in $\alpha\mu$. (5) For $1 > \alpha\mu > 0$, T^{2*} increases with increased variance of the value of the asset.*

Result (1) demonstrates the pivotal role of information in the price–quantity relationship. In our model, only information can induce a spread; liquidity or price pressure has no effect on prices because by assumption inventory has no effect on prices. This information effect arises from both the uncertainty surrounding an information event (α) and the uncertainty regarding any individual's trading motivations (μ). If there is any possibility that trading is information-related ($\alpha\mu > 0$), a spread must develop to offset the losses market makers will incur in trading with the informed. The larger the trade size, the greater will be this loss and, as a result, large quantities must trade at less favorable prices.

Proposition 6 also suggests that one should be cautious in any attempt to infer the market price, or a good proxy for it, from transactions data. As the model demonstrates, there is no one market price; the price per share depends on the quantity traded. If the desired proxy is V^*, then only the small-trade price in a separating equilibrium actually reveals this. Since spreads need not be symmetric around V^*, it is not correct simply to use the midpoint of the spread as the market price. If there are more block sales than block buys and high and low signals are equally probable, the midpoint of the large-trade spread overestimates V^*. Since there are typically more block sales than block buys, this suggests that empirical research using average prices will yield biased results.

Our results that the spread T^{2*} decreases with increased depth and increases with increased variance are consistent with the conclusions reached by Copeland and Galai (1983) and with empirical results in numerous papers [see, for example, Tinic and West (1973)]. As we demonstrate in the next section, our results on the role of information in the price–quantity relationship provide an explanation for the observed price behavior around block trades.

5. The price effects of block trades

Our analysis demonstrates that large trades are made at less favorable prices. Although empirical research confirms this result [see Kraus and Stoll (1972), Dann, Mayers and Raab (1977), Smith (1986)] previous work also provides the intriguing result that large blocks have *persistent* price effects. In particular, transaction prices are lower after block sales and higher after block buys, with only a partial reversion to their prior levels. In this section, we provide one explanation for this price phenomenon. We demonstrate that the information conveyed by a block trade alters the price path.

To investigate the price effects of block trades, we must extend our model to incorporate a sequence of trades. This, in turn, requires an analysis of how market makers incorporate information learned from previous trades into their pricing strategy for future trades. Since trades can be information-based, the pattern of trades reveals something about the presence (and information) of informed traders.

Following a trade at $t = 1$, market makers set their trading prices for $t = 2$. Each market maker again determines the conditional value of δ, where this conditional expectation now depends on both the type of trade and the past trades. This changes the updating formula given by (1) to

$$\begin{aligned}\delta_2(Q_1, Q_2) &= \Pr\{V = \underline{V} | Q_1, Q_2\} \\ &= 1 \cdot \Pr\{s = L | Q_1, Q_2\} + 0 \cdot \Pr\{s = H | Q_1, Q_2\} \qquad (13) \\ &\quad + \delta \cdot \Pr\{s = 0 | Q_1, Q_2\},\end{aligned}$$

where $Q_2 \in [B^1, B^2, S^1, S^2]$ is the desired trade at $t = 2$. Given the appropriate δ_2, prices for each possible trade can be determined.

One implication of (13) is that prices differ depending upon which trade actually occurred at $t = 1$. To focus on the price effects of a block trade, let this $t = 1$ trade be a block sale, S^2. Suppose that the market is in a separating equilibrium, so that the block sold at price b_1^2, defined in (5) (for notational simplicity we suppress the *).[8] To determine the small-trade prices for period 2, each market maker calculates $\delta_2(S^2, S^1)$ and $\delta_2(S^2, B^1)$, or the conditional

[8] The price revision following block or small trades depends primarily on the probability of informed trading. In a separating equilibrium, the informed trade only large quantities. In a pooling equilibrium, they trade both quantities, but the probability of trading with an informed trader is always greater at large quantities. (Otherwise, the price for small quantities would be further from V^* than the price for large quantities.) As a result, the analysis in a pooling equilibrium is similar to the analysis for a separating equilibrium. Moreover, our results on the price effects of a block trade hold in either equilibrium.

probabilities that $V = \underline{V}$. These are given by

$$\begin{aligned}
&\delta_2(S^2, S^1)\\
&= \delta_2(S^2, B^1)\\
&= \frac{\alpha\delta\left[\mu + (1-\mu)X_s^2\right](1-\mu) + \delta(1-\alpha)X_s^2}{\alpha\delta\left[\mu + (1-\mu)X_s^2\right](1-\mu) + \alpha(1-\delta)(1-\mu)^2 X_s^2 + (1-\alpha)X_s^2},
\end{aligned} \tag{14}$$

so that the block trade at time 1 affects both conditional expectations equally. Indeed, it is easy to demonstrate that

$$\delta_2(S^2, S^1) > \delta \quad \text{if} \quad \alpha\mu > 0. \tag{15}$$

Thus, the market maker places a greater probability on $V = \underline{V}$ if there is any chance that the block trade at time 1 was information-based. Since the zero-profit constraint again dictates prices equal to the conditional expected value, this implies that, for $\alpha\mu > 0$,

$$a_2^1(S^2) = b_2^1(S^2) = \underline{V}\delta_2(S^2, S^1) + \bar{V}\left(1 - \delta_2(S^2, S^1)\right) < V_1^*, \tag{16}$$

where V_1^* is the $t = 1$ small-trade price.

Eqs. (15) and (16) dictate that, following a block sale, the market maker sets a *lower* price for the next small trade. As before, the bid and ask prices for small trades are equal but, provided $\alpha\mu > 0$, these small-trade prices at $t = 2$ are strictly less than small-trade prices at $t = 1$. Indeed, it is easy to show that the new large-trade prices are also lower than their corresponding $t = 1$ levels. Because of the possibility that the block sale was triggered by adverse information about the stock's value, market makers adjust their trading prices.

How much these prices fall depends on the dual information effects captured by α and μ. Although the new small-trade price, $b_2^1(\cdot)$, is below the previous small-trade quote, it is not clear how $b_2^1(\cdot)$ relates to the last transaction price (i.e., the block trade), $b_1^2(\cdot)$. In particular, will prices recover after a block trade or simply remain at the new lower level? To determine this, recall that

$$b_2^1(\cdot) = \underline{V}\delta_2(S^2, S^1) + \bar{V}\left(1 - \delta_2(S^2, S^1)\right),$$

and

$$b_1^2(\cdot) = \underline{V}\delta_1(S^2) + \bar{V}\left(1 - \delta_1(S^2)\right). \tag{17}$$

How these prices relate, therefore, depends on the probabilities the market maker attaches to $V = \underline{V}$. For prices to recover [i.e., $V_1^* > b_2^1(\cdot) > b_1^2(\cdot)$], it must be true that $\delta_2(S^2, S_2^1) < \delta_1(S^2)$ or that

$$\delta \frac{\alpha[\mu + (1-\mu)X_S^2](1-\mu) + (1-\alpha)X_S^2}{\alpha\delta[\mu + (1-\mu)X_S^2](1-\mu) + \alpha(1-\delta)(1-\mu)^2 X_S^2 + (1-\alpha)X_S^2}$$

$$< \delta \frac{\alpha[\mu + (1-\mu)X_S^2] + (1-\alpha)X_S^2}{\alpha\delta[\mu + (1-\mu)X_S^2] + \alpha(1-\delta)(1-\mu)X_S^2 + (1-\alpha)X_S^2}. \tag{18}$$

This will be true if both $\alpha\mu > 0$ and $\alpha < 1$.

The conditions derived above provide some interesting insights into the price effects of block trades. As before, for prices to change at all, it must be possible for trades to be information-based. If $\alpha\mu = 0$, trades can have no information content and therefore no effect on prices. The condition that $\alpha < 1$ is more intriguing. If market makers know that an information event has occurred (i.e., $\alpha = 1$), it is easy to show that $b_2^1(\cdot) = b_1^2(\cdot)$, or that prices do not recover. With the only uncertainty being who is informed (the μ), a small trade provides no information to the market makers. As a result, the next small-trade price is set equal to the previous expected value, which is just the block price.

If market makers face the added uncertainty of whether an information event has occurred ($\alpha < 1$), however, this is no longer true. Now a small trade following a block sale provides information because a small trade reduces the likelihood the market maker attaches to an information event having occurred. Specifically, the small trade causes market makers to put more weight on their original probability of $s = L(\delta)$. When the small trade is the initial trade of the day, this results in no change in prices because these prices are already based on δ. Now, however, a block sale at time 1 changes the market makers' expectations of $s = L$, with δ moving to $\delta_1(S^2)$. A small trade at $t = 2$ causes each market maker to place more weight on δ and less on $\delta_1(S^2)$. Since $\delta_1(S^2) > \delta$, this causes a partial recovery of trading prices following a block sale.

Figs. 1 and 2 illustrate these information effects on transaction prices. Fig. 1 depicts the price path for a small-trade, block-sale, small-trade sequence when there is trader-related uncertainty only. The block trade causes the price to fall and to remain lower for subsequent trades. Fig. 2 depicts the price path for the same trade sequence when there is both trader and event uncertainty. Again, the block trade causes prices to fall, but now there is a partial recovery in the security price. The latter graph is consistent with the empirical results of Kraus and Stoll (1972) and Dann, Mayers and Raab (1977).

Our analysis demonstrates, therefore, that information affects the price–quantity relationship in a complex manner. If market makers could

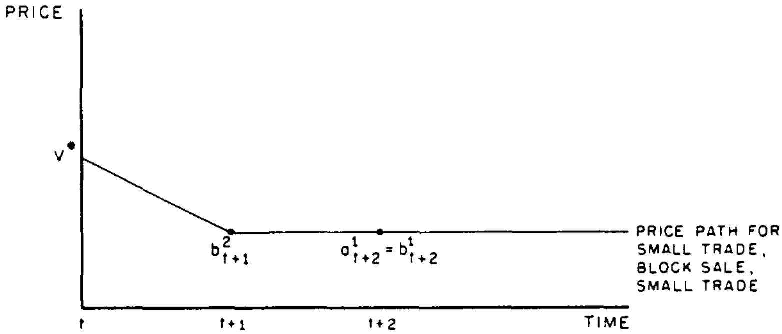

Fig. 1. The time path of market maker quotes and transaction prices in a separating equilibrium when there is trader-related uncertainty only. Market makers know that an information event has occurred but they do not know what it was or who is informed. At time t there is a small trade at the prior expected value of the asset, V^*. At time $t+1$ there is a block sale at the bid price, b^2_{t+1}, for a large scale. At time $t+2$ there is a small trade at $b^1_{t+2} = a^1_{t+2}$, the common bid and ask price for small trades.

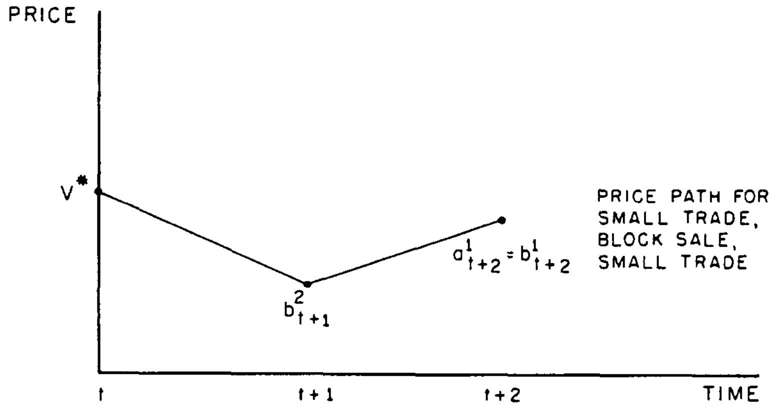

Fig. 2. The time path of market maker quotes and transaction prices in a separating equilibrium with both trader and event uncertainty. Market makers do not know whether an information event has occurred, or what it was and who observed it if it has occurred. At time t there is a small trade at the prior expected value of the asset, V^*. At time $t+1$ there is a block sale at the bid price, b^2_{t+1}, for a large scale. At time $t+2$ there is a small trade at $b^1_{t+2} = a^1_{t+2}$, the common bid and ask price for small trades

know when information events occur, the uncertainty about whether any individual trader is informed could be handled by simply setting less favorable prices for large quantities. Since informed traders' profits are increasing in quantity for any given price, this pricing strategy counters the adverse selection problem that arises with trade size. If, more realistically, market makers do not know when such information events occur, this simple pricing strategy is no longer optimal. Now trade size matters not only because it is correlated with a trader's information but also because it signals the existence of an information event. Consequently, both the size and the sequence of trades matter in determining the price–quantity relationship. As we have demonstrated, it is these dual information effects that provide an explanation for the observed price effects of block trades.[9]

6. The empirical behavior of security prices

In previous sections, we developed an information-effects theory of the price–quantity relationship. One result of our analysis is to provide an information-based explanation for the price effects of block trades. It would be useful, however, to delineate how the predictions of our theory differ from those of the liquidity-premium or inventory theory and to identify what our model suggests for the empirical properties of security price behavior. In the following analysis, we use our result that the price–quantity relationship depends on both the size and the sequence of trades to address these issues.

In our model, a security's quotes always reflect the market makers' perception of the value of the underlying assets. The price of the transaction at time t, p_t, is one of the equilibrium bid or ask prices for a small or large trade. We know from section 3 that each of these prices is the market makers' expectation of the value of the security conditional on prior information and the quantity of the trade at time t. This prior information is the sequence of past trades $\{Q_\tau\}_{\tau=1}^{t-1}$, where $Q_\tau \in [B^1, B^2, S^1, S^2]$ for each τ. Let $I_t = \{Q_\tau\}_{\tau=1}^{t}$ represent the market makers' time t information. Then $p_t = \mathrm{E}[V|I_t]$. Because security prices are conditional expectations with respect to I_t, they form a martingale relative to the market makers' information.

Proposition 7. *The stochastic process $\{p_t\}$ is a martingale relative to I_t.*

Proof. It is sufficient to show that for any t and p_t, $\mathrm{E}[p_{t+1}|I_t] = p_t$. We know from section 3 that $p_t = \mathrm{E}[V|I_t]$. So $\mathrm{E}[p_{t+1}|I_t] = \mathrm{E}[\mathrm{E}[V|I_{t+1}]|I_t]$. But, since $I_{t+1} = (I_t, Q_{t+1})$, we have $\mathrm{E}[\mathrm{E}[V|I_{t+1}]|I_t] = \mathrm{E}[V|I_t] = p_t$. Q.E.D.

[9] Throughout our analysis, we assume that all block transactions are handled only by market makers. In actual security markets, many large blocks are arranged off the floor by intermediaries known as block traders. In these trades, a syndicate of buyers is formed before the trade is taken to the floor of the exchange for execution. Our result of this syndication process is that the market maker takes only a small piece of the trade, with a consequent small effect on his inventory position. Given this limited role, an inventory-based explanation for the price effects of block trades seems unlikely to provide much insight. This trading-venue problem does not affect the information-based explanation of block trades. Whether the market maker takes all, part, or even none of the trade himself is irrelevant, since it is the existence of the trade that influences the prices at which he will buy and sell subsequent quantities of the stock. For more discussion of the block trading process, see Burdett and O'Hara (1987).

Because prices follow a martingale relative to some information, they also follow a martingale relative to the set of past prices. That is, $p_t = E[p_{t+1}|p_t, p_{t-1}, \ldots, p_1]$. This means that, in relation to publicly available transaction-price data, the market is a fair game.

One important characteristic of the information-effects model, however, is that the entire sequence of past trades is informative about the likelihood of an information event. Because the likelihood of an information event affects prices, this means that the *entire sequence* of trades matters in determining prices. To calculate the distribution of the next trade price, p_{t+1}, therefore, we need to know not only the current price, p_t, but also how the market got to the current price. As a result, prices typically will not follow a Markov process. Further, since the likelihood of an information event is not just a function of the sum of past trades, prices and the market makers' inventory position together will not typically follow a Markov process. Let G_t be the market makers' inventory position at date t.

Proposition 8. If $0 < \alpha\mu < 1$ *and* $X_S^1, X_S^2, X_B^1, X_B^2 > 0$, *the stochastic processes* $\{p_t\}_{t=1}^{\infty}$ *and* $\{p_t, G_t\}_{t=1}^{\infty}$ *are not Markov.*

Proof. A stochastic process $\{z_t\}_{t=1}^{\infty}$ is Markov if and only if the distribution of z_{t+1}, conditional on z_t, is independent of $z_{t-1}, \ldots, z_1$. We prove the proposition by constructing a sequence of trades for which this is not true. We consider the case of a market in a separating equilibrium at time 1, i.e., where inequalities (8) and (9) are satisfied. The analysis of the other case is symmetric.

Fix an integer n so that $(n-m)S^1 = mB^1$ for some integer m. This can be done since S^1 and B^1 are integers. Suppose that the first n trades consist of $(n-m)$ sales of S^1 and m buys of B^1. This event has a positive probability if $X_S^1, X_B^1 > 0$ and $\alpha < 1$ or $0 < \mu < 1$. Then the market makers' inventory position just before time $n+1$ is the same as it was just before time 1. Further, since a string of small trades starting at time 1 does not affect expectations, the price of each of the n trades is V^*. Thus, if $\{p_t\}_{t=1}^{\infty}$ or $\{p_t, G_t\}_{t=1}^{\infty}$ is Markov, the distribution of p_{n+1} [or (p_{n+1}, G_{n+1})] must be the same as the distribution of p_1 [or (p_1, G_1)].

However, it is easy to calculate that the market maker's expectation of the probability of an information event is $\Pr\{s \in \{H, L\}: (p_n, G_n), \ldots, (p_1, G_1)\} = \alpha[(1-\mu)^n/[\alpha(1-\mu)^n + (1-\alpha)]] < \alpha$ if $\alpha\mu > 0$. But, it follows from (5) and (6) that, as $0 < \delta < 1$ and $X_S^2, X_B^2 > 0$, bids for large trades rise and asks for large trades fall as the probability of an information event falls. [These are the appropriate pricing equations for date n, since δ is unchanged by an initial string of small trades and the inequalities (8) and (9) remain satisfied.] So the distribution of prices, or prices and quantity, at date $n+1$ cannot be the same as at date 1. Q.E.D.

This prediction is quite different from the predictions generated by the inventory or liquidity-effects model. In an inventory model, to calculate the distribution of the next price, it is sufficient to know only the market maker's inventory position (or, equivalently, his last price). As a result, in this model, prices and inventory will follow a Markov process.

Whether prices (or prices and inventory) follow a Markov process has important implications for the empirical behavior of security prices. For example, suppose a market maker is at his preferred inventory level and has some expectation, denoted V^*, about the asset's true value. If the $t = 1$ trade is a block sale, will the market maker set a price of V^* for a similar-sized block buy at $t = 2$? In the pure liquidity premium or inventory theory, the answer should be yes. Since the block buy returns the market maker to this preferred inventory level, he should be willing to pay the price consistent with this level, V^*. Indeed, this same price should also result if the trade sequence was instead block buy, block sale. In either sequence, the market maker's ending inventory position is the same, and so too should be his trading price. With security prices following a Markov process, the sequence of trades is not important to the price path.

This is not true in the information-effects theory. Given a block sale at time 1, it is easy to demonstrate that the block-buy price at time 2 is strictly greater than V^* if $\alpha\mu > 0$ and $\alpha < 1$. Conversely, given a block buy at time 1, the block-sale price at time 2 is strictly less than V^*. Because the market makers use the trading sequence to infer the probability that an information event occurred these price paths both differ from that predicted by a pure inventory-based theory.

Our prediction that security prices will not follow a Markov process should be of interest to researchers using transaction-price data. If our theory is correct, it is the sequence of transaction prices, and not individual data points, that is informative. This suggests, for example, that empirical research on the price-quantity relationship should consider the sequence of trades preceding a block, and not merely the block trade itself, to identify the price effects of large trades.

7. Conclusions, qualifications, and extensions

We have attempted to develop a formal model of the effect of information on the price–trade size relationship. Our goal in doing so is not to claim that the price–trade size relationship is due solely to information, but rather to demonstrate those phenomena that are consistent with information effects. Our view is that security prices respond to a number of factors, including inventory, transactions costs, and risk aversion by market participants. Before a definitive model of security-price behavior can be developed, however, we must understand how each of these factors can affect prices. Our analysis of the role of information is a start in this direction.

Because the model we analyze is highly structured, several of its features deserve comment. First, since our interest is in the price effects of block trades, we have to quantify block versus small trades. We analyze the simplest structure consistent with block trades having information content – two signals and two trade sizes. Certainly, one extension of the model is to consider multiple signals and trading sizes, but it is not clear what substantive gains in insight this would produce. Another extension is to incorporate traders' reputations. Clearly, a large trader would benefit if he could convince the market maker that he is uninformed, since he could then trade at the same prices as a small trader. Institutional traders who follow programmed trading may succeed at developing a reputation for being uninformed, but the potential for building, and exploiting, such a reputation is limited by the informed traders' ability to mimic the behavior of uninformed traders.[10]

Second, several elements of our model are treated as exogenous whereas in a more complete analysis they would be endogenous. Our uninformed traders trade large or small quantities for exogenous reasons. It is possible to have these traders respond to prices and to learn along with the market makers, but this adds considerable complexity and little insight. We also take the trading frequency (or intensity) of the informed, μ, and the probability of an information event, α, as exogenous. If information events occur, in part, because traders search out information, then α, and perhaps μ, adjusts to equalize across markets the net benefit of becoming informed. Calculating the benefit to any trader of becoming informed, however, requires specifying the trading protocol in great detail. Since trading institutions differ in design, it is not clear exactly how this should be done. If α and μ are endogenous, their equilibrium levels depend on factors such as the variance of the asset's value, the ability of the market to accommodate frequent trades, and the order size that can be traded. Thus, conclusions about the effects of these variables should be treated with caution. They are partial equilibrium conclusions.

Third, we assume that informed traders agree about the expected value of the asset. If they see different signals, or interpret signals differently, the analysis is more complicated. In this case, the fraction of informed traders who trade at any price could vary continuously with the price. This makes the calculation of equilibrium prices more difficult, but should not change the nature of our results.

Fourth, both market makers and the informed are assumed to behave risk-neutrally. The risk neutrality of the informed is used to provide clear conditions for pooling and separating equilibria. It can easily be relaxed. The risk neutrality of market makers is important for our results. Risk-averse market makers would take their inventory position into account when de-

[10]An institution may benefit from a reputation with market makers as being uninformed, but it presumably would not care to have this reputation with its own investors.

termining prices. We use risk neutrality to provide a clear contrast to the inventory model.

Finally, we assume that informed traders behave competitively. For alternative approaches, see Kyle (1985) and Grinblatt and Ross (1985). This assumption is important for our results, but it is standard for markets with a large number of similar traders. Competitive behavior ensures that each informed trader maximizes expected profit trade by trade. Determining whether this is optimal behavior requires a more complete description of the trading protocol. If there is a large number of informed traders, however, each of them is likely to have little effect on the price of his future trades.

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