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ESSAYS ON THE ROLE OF TIME
IN PRICE DISCOVERY

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Essays on the Role of Time in Price Discovery

Key words: ACD, GARCH, Transactions Data, Market Microstructure Theory

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To
Beverly Dina Ben Sita

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**I Part:
Conceptual Thoughts**

1. Introduction

Financial markets play a key role in modern economy. Financial markets encourage investment by providing places for investors and financiers to meet, and provide financial solutions to investment problems. It is even said that financial markets aggregate and allocate resources and risks more efficiently in time and space. In order to understand financial markets, we need to examine the behavior of the participants in these markets. Hence, it is no longer sufficient to understand how financial markets increase wealth. We have also to understand how trades are executed and paid for, the costs of trading, and how trading is regulated and monitored in these markets (McInish (2000)). These issues are extensively treated in the finance field called market microstructure.

Garman (1976) coined the term market microstructure that is associated with trading mechanisms, and information structures in the short-run. The microstructure theory is a theory on price formation (O'Hara (1995)), less restrictive than the theory on price completeness (Fama (1970)). By the loop of the microstructure theory, the process of price formation can be defined, measured and examined. Recently, the growth of interest in microstructure theories has been fueled by the increasing availability of transactions data. A good illustration of this is the Engle (2000) study where the term ultra-high frequency data for transactions data appears for the first time. However, this type of data requires relatively new economic theories and econometric models (Aït-Sahalia et al. (2004)).

The theory on transactions data is a theory on the flow of information, trading frictions and microstructure noise. However, the portion of microstructure noise is substantial for price changes over tiny time interval (Aït-Sahalia et al. (2004)). Thus, the systematic behavior in the short-run pattern of prices is difficult to obtain through price changes. Hence, transactions data arises questions on its relevance, reliability and regularities. Traders and academics are interested to know in which ways transactions data improves the measurement of liquidity and volatility. Since price changes over very short time intervals are unable to fully capture the volatility and the liquidity pattern of price changes, a promising role has been attributed to transaction time. Therefore, this dissertation investigates the role of transaction time in the evolution of prices in the short-run.

1.1 Research Areas

A general view in economics is that prices at equilibrium of the supply and the demand favor both sellers and buyers¹. However, equilibrium is a result of structural and trading factors. Some of these factors are observable. For unobservable factors, it is a common practice to use proxies. The resolution to use transaction time as a proxy for the rate of information arrival is motivated by the complexity of information with indistinguishable features in the short-run. Easley and O'Hara (1992) provide a theory on the role of time in the process of price formation. Engle and Russell (1998) provide a model for transaction time demonstrating that transaction time reverts into trading intensity. Hence, there are theoretical and econometric materials to examine (1) the stochastic process of transaction time, (2) the revision and the learning element of transaction time, and (3) the role of transaction time in the evolution of prices. The three research questions are related to (1) the flow of information in the market, (2) the distribution of information among traders, and (3) the information content of a transaction, respectively.

1.2 Research Focus and Relevance

The purpose of this dissertation is to investigate the role of transaction time in the evolution of prices in the short-run. The focus here is the extent to which transaction time presents (i) autoregressive regularities, (ii) reveals information to traders, and (iii) impacts the evolution of prices. The first focal point is intended to link the econometric on the conditional risk to the theory on the transaction time. The second focal point is intended to bridge the learning and the revision element of the transaction time and the market microstructure theory. The third focal point is intended to bridge the random walk theory and the market microstructure theory. The first focal point is examined in the first essay of the dissertation, the second focal point is examined in the second essay of the dissertation and the third focal point is examined in the third essay of the dissertation.

¹ This type of equilibrium for which there is a single market-clearing price is referred to as Walrasian equilibrium, thus all buyers and sellers who are willing to trade at the established price are accommodated in a Walrasian market (McInish (2000)).

This dissertation differs from previous microstructure studies in the following three aspects. First, the dissertation considers the stochastic process of trade durations² regarding the regularities of the autoregressive conditional heteroskedasticity (ARCH) structure of Engle (1982), the learning and the revision element due to trade durations, and the role of trade durations in the formation of prices. It appears from microstructure studies that the variance and the covariance of stock returns are biased due to trading frictions and market imperfections such as the price discreteness and the bid-ask spread bounce. In this respect, trade durations are robust to many market imperfections that contaminate the variance and the covariance of stock returns (Harris (1990)).

Second, the three essays of the dissertation investigate either the role of the trade duration in explaining trading behaviors or the role of the trade duration in price discovery.

Essay (1) examines the relationship between the trade duration and the stock return volatility relative to the sign of the return shock, the magnitude of the return shock and the intensity of the trade. Hence, essay (1) extends the Engle (2000) model by examining the relationship between the trade duration and the stock return volatility relative to the sign of the shock. Furthermore, essay (1) compares three autoregressive conditional duration models by using the duration impact curve that reveals the prediction pattern of each of the three models.

Essay (2) develops two complementary econometric approaches. The first approach searches to determine the direction of the causal relation between trading volumes based durations and the stock return variance. The second approach is subsequent to the first approach and describes the evolution of prices in short-run from its strongest link. Essay (2) contributes to the present literature essentially by developing a structural model that describes the evolution of price in the short-run relative to the variance, the revision and the learning dynamic. The essay documents that the stock return and the variance are increasing in the size of the transaction (Easley and O'Hara (1987)), and supports the theory of Easley and O'Hara (1992) that time is correlated with the value of the asset.

² Trade (transaction) duration is the difference in seconds between two successive trade times.

Essay (3) investigates the role of trade durations in the evolution of price within a structural model combining elements of the random-walk theory and of the market microstructure theory. The essay extends the Hasbrouck (1991) and the Dufour and Engle (2000) model by including trade duration as a trading factor in the case of Hasbrouck (1991) and motivating the use of trade duration as a trading factor relative to price discovery in the case of Dufour and Engle (2000). The model shows that the autocorrelation structure of the order flow is the most important determinant of the covariance bias of the stock return. The empirical tests show that the impact of a trade on prices is associated with the process of price formation through the pattern of the order flow, the trade duration and the size of the trade.

Third, this dissertation uses data from a limit order market. Trading with consolidated limit orders is characterized by uncertainty on price, quantity, traders' identity, and the execution time. Comparative studies to this work use mostly data from the New York Stock Exchange, which in opposite to a limit order book system such as the Helsinki Stock Exchange, minimizes considerably the execution risk due to the absence of a partner at the other side of the trade to trade with and the adverse selection risk due to a longer exposition in the book while waiting for a probable trader that can use the latest public information.

1.3 The Organization of the Dissertation

This dissertation is organized as following. The first part of the dissertation provides a general introduction to the dissertation. The introductory part overviews essentially the theory of time and price in microstructure studies. The second part of the dissertation contains three essays on the role of trade durations in the process of price formation. Essay (1) examines essentially the relationship between trade durations and the conditional returns variance. Essay (2) examines the effects of trading volume on stock return volatility. Finally, essay (3) examines essentially the role of trade durations in price discovery.

2. The Role of Time in Price Revisions

Ordinarily time is assumed to be constant in financial and econometric models. Several studies of financial market behavior rely on price observations drawn at fixed time intervals. The advent of transactions data has changed this view since a fundamental property of transactions data is that observations occur at varying time intervals. Indeed, a classical assumption of asset pricing models is that prices are random and continuous. The randomness of prices means that they may arrive at any time within a very short period of time. However, prices do not change notably at each point of time. Hence, trade durations may be useful to study the evolution of prices at arbitrarily high frequencies.

2.1 Clock Time Versus Transaction Time

A clear distinction must be made between clock time with interesting implications in physics, and transaction time, which is the time for market administrators to organize trading in the market, and for traders to enter or to exit the market. For example, in Admati and Pfleiderer (1988) model, liquidity traders choose carefully the time to enter the market since they lack information, and do not know when new information arrives in the future. Therefore, transaction time appeals two important questions: (1) when to enter (to exit) the market, (2) and how long to stay in the market. The first question is related to this work. The second question covers a large portion of financial studies on investment at longer horizon.

The question about the time to enter (to exit) the market can be related to the market microstructure theory on liquidity and price discovery. Goodhart and O'Hara (1997) point out that prices are not Markovian, thus the sequence of prices matters, and hence requires estimation based on the entire history of prices. They further argue that time is endogenous, thus transactions are more likely to occur when there is new information. Engle and Russell (1998) revert the time process into a volatility process; demonstrating that time dependence affects the process of security prices. They refer to their model of time process as the Autoregressive Conditional Duration (ACD) model. The ACD model provides an alternative measure to volatility in that the intensity of price changes captures the variability of the order process.

2.2 Time in Microstructure Models

In the standard microstructure models, time plays no role. In Garman (1976), the arrival intensities for buyers and sellers are related to the dealer's price. In this model, a large spread increases the revenue per buyer-seller pair but decreases the number of traders per unit time. In Amihud and Mendelson (1980), the rate of failure is a function of an active inventory control in the sense that a dealer determines the bid-ask spread relative to his preferred inventory position. In both Garman (1976), and Amihud and Mendelson (1980), the process of time is not autoregressive; rather it follows a Poisson process with a constant intensity parameter.

In Glosten and Milgrom (1985), randomly selected traders arrive at the market singly, sequentially, and independently without any reference to the influence of time in trading behaviors. In Kyle (1985), all trades are batched so that when individual orders arrive is not relevant to the market maker. In Admati and Pfleiderer (1988), liquidity traders avoid informed traders by choosing carefully the time at which to trade. In Easley and O'Hara (1987), only the size of the transaction is an important vector of information. In Madhavan (1992), the degree of market failure is related to the degree of information asymmetry, which depends on other variables exclusive time with not stochastic inference on the behavior of the asymmetry. Hence, Glosten and Milgrom (1985), Kyle (1985), Admati and Pfleiderer (1988), Easley and O'Hara (1987), and Madhavan (1992) do not consider time as a vector of information for sequential learning and strategic trading.

However, in Diamond and Verrecchia (1987), transaction time has implication on the perception of traders on the essence of the information. The argumentation is constructed on the short-selling theory. The authors argue that price would converge rapidly to its true value if traders are given the opportunity to trade at any time, thus forcing traders to do not sell when they should, is a sign of "bad" news. In Easley and O'Hara (1992), time affects prices as time reveals information-based periods. In contrast to Admati and Pfleiderer (1988), where liquidity traders enter the market discretionary, in Easley and O'Hara (1992), informed traders enter the trading game, sporadically and advantageously.

2.3 Time in Different Trading Venues

Transaction time has different implications on different trading systems since trading is accomplished according to certain pre-established rules proper to each financial market and system. The structure form of financial markets varies considerably both between markets and over time as a market evolves. In this respect, there are two important types of continuous trading systems that can be opposed to each other, namely, a dealer market of the type of the New York Stock Exchange and a limit order book market of the type of the Helsinki Stock Exchange. In the former, the specialist posts bid and ask quotes, and is directly confronted with the aggressiveness of private information. In the later, a trader chooses between submitting a limit order or a market order using the service of a broker with no obligation to provide liquidity to informed traders.

Hence, trading mechanisms will particularly differ in the time trade can occur, about the aggressiveness of private information, and about the transaction size (Madhavan (1992)). Furthermore, trading mechanisms will have an impact on traders' attitude toward risk. In Viswanathan and Wang (2002), a risk-neutral trader chooses to trade in a limit order book with greater price competition, whereas a risk-averse trader prefers a dealership market with higher capacity to absorb large transaction quantities. In Foucault (1999), traders who choose to submit limit orders run the risk to trade with traders taking advantage of the latest available public information. Since in a limit order book market, traders do not trade with a designated specialist, the duration between two successive transactions or the duration between two successive trading events will tend to be longer. Hence, under information asymmetry, the quantity of liquidity to consume at time t will be insufficient, thus the rapidity with which prices are supposed to react to new information will be hampered. In conclusion, in a limit order book market the absence of trades indicates both that there is no liquidity to consume (the absence of a trader taking the other side of the trade) and that there is no superior information to fear³.

³ The claim that the absence of trades is a sign that there is no news means that information is viewed as transitory, thus informed traders cannot wait longer than necessary. It is even expected that informed traders would maximize the transaction quantity for each piece of superior information they might possess (Easley and O'Hara (1987)).

2.4 The Helsinki Stock Exchange

The History of the Helsinki Stock Exchange (HEX) casts its roots in 1912 with the first transaction occurring on October 7, 1912. Until 1983, the HEX was operating as a financial association. In 1984, the HEX adopted a cooperative statute, abandoning its free form association statute. In 1995, the HEX was registered as a limited liability company. In 1997, the HEX merged with several clearing and stock deposit companies and associations. In 1998, the HEX merged with the Finnish Central Securities Depository to form the Helsinki Exchanges Group Plc. During 2001 and 2002, the HEX acquired a majority of share of the Tallinn Stock Exchange and the Riga Stock Exchange. In 2003, the OM-group purchased the HEX.

The development of the HEX is due both to the introduction of the electronic trading system in 1989 and its rapid internationalization and standardization to worldwide financial practices. Hedvall (1994) provides and discusses different materials of price discovery in the early 1990's. From a global perspective, the HEX is relatively small and comprises mostly domestic stocks of which Nokia is the largest and accounts for one third of the total capitalization of the HEX. The HEX comprises three different trading lists, which are 1) the official list containing the Finnish blue-chip companies, 2) the I-list containing middle-sized companies, and 3) the NM-list containing growing and innovative companies.

Being an order-driven electronic market, price discovery in the HEX is a result of a trading game between individual traders who use the service of broker-dealers with no obligation to provide liquidity to informed traders. During the continuous session⁴, the trading system matches automatically into deals the bids and offers by individual traders. However, the matching process is executed first by price priority and second by time priority. The settlement occurs in three days following the transaction day, and shares are deposited on an account in a central security deposit. The Financial Supervision Authority (FSA) oversees financial transactions and the behavior of market participants in the HEX.

⁴ Nowadays, the continuous session is held between 10.00 a.m. and 6.20 p.m.

3. The Market Microstructure and the Random-Walk Theory

Liquidity can be defined as the ability to buy or to sell an asset readily, at low cost and without substantial impacts on prices. Price discovery can be defined as the efficient and timely incorporation of the information implicit in investor into trading in market prices. The random walk is a fundamental theory on the process of prices that should be efficient in time, place, magnitude, and sign. O'Hara (2003) discusses the market microstructure theory of liquidity and price discovery. Hasbrouck (2002) discusses the random walk theory of microstructure prices.

3.1 Liquidity

Asset pricing models repose on the information symmetry hypothesis according to which all traders share virtually the same information regarding the asset's expected risk and return at the clearance time under the supervision of an auctioneer. Further, asset pricing models presume the existence of liquidity that is proportional to the level of information symmetry. However, microstructure studies postulate that liquidity is proportional to the degree of information asymmetry, thus there is always a group of traders that cannot diversify the liquidity risk in the simplest way as the Capital Asset Pricing Model (CAPM) suggests.

In the CAPM, the systematic risk moves with the entire economy and liquidity risk is viewed as idiosyncratic, which can be diversified away. In contrast, the microstructure theory views liquidity risk as systematic since liquidity is associated with the matching process of buyers and sellers. In Black (1986), the role of liquidity is so important that the market closes in the absence of liquidity. In Madhavan (1992), the role of trading mechanisms is so central that the presence of traders in time and space determines the degree of information asymmetry. In Amihud (2002), traders will demand a "systematic" premium for providing liquidity, as excess stock returns are an increasing function of expected illiquidity. In Acharya and Pedersen (2003), a security's required return depends on its expected illiquidity and on the covariances of its own return and illiquidity with market return and market illiquidity. Hence, liquidity is priced for (i) security and market illiquidity, and (ii) security and market expected return and risk.

3.2 Price Discovery

In many economic settings, the value of something is often thought to possess private and common components. Private values are said to be idiosyncratic and are revealed to market agents through trading. Common values are said to be common knowledge about a security value. In microstructure market theories, the realisation of common values is a result of a trading game that involves agents with private information, agents without information, and market makers with obligation, under certain conditions and market structures, to provide liquidity. Hence, market makers quote bid prices for agents who want to sell and ask prices for agents who want to buy. The difference between the bid and the ask price is the bid-ask spread that represents the compensation of market makers such as:

$$B_t = M_t - C , \quad (1a)$$

$$A_t = M_t + C , \quad (1b)$$

where B_t is the bid price at time t , A_t is the ask price at t , M_t is the trade price at t , and C is the per-trade cost. Equations (1a) and (1b) say that an agent who want to buy must pay the market maker's ask price, and an agent who want to sell must pay the market maker's bid price. Since M_t is unobservable, the market maker has to be guided by a set of variables that help him to determine a regret free bid-ask spread as demonstrated powerfully by Glosten and Milgrom (1985). To see this, equations (1a) and (1b) can be rewritten as:

$$P_t = M_t + q_t C , \quad (1c)$$

where P_t can be A_t or B_t , and q_t is the trade indicator taking +1 if the agent is buying and -1 if the agent is selling. It follows that the per-trade cost is

$$C = \frac{P_t - M_t}{q_t} . \quad (1d)$$

Equation (1b), (1c) and (1d) assumes that C is constant, q_t is an identical and independent sequence, and P_t is continuous. However, the observation of the data suggests that C is not constant, q_t is serially dependent, and P_t is discrete and serially dependent. Hence, price discovery suffers from trading frictions, market

imperfections, and information asymmetry. The Roll (1984) model describes quite well the different components of equation (1c), which can be written in terms of the first difference of P_t such as:

$$\Delta P_t = C\Delta q_t + u_t, \quad (1e)$$

where $\Delta P_t = P_t - P_{t-1}$, $\Delta q_t = q_t - q_{t-1}$ and $u_t = M_t - M_{t-1}$. Assuming that $E[u_t] = 0$, the first moment, the variance and the first-order autocovariance of ΔP_t are:

$$E[\Delta P_t] = E(u_t - C\Delta q_t) = CE[\Delta q_t]. \quad (1f)$$

$$Var(\Delta P_t) = \sigma_u^2 + Var(\Delta q_t)C^2. \quad (1g)$$

$$Cov(\Delta P_t, \Delta P_{t-1}) = C^2 E(q_t - q_{t-1})(q_{t-1} - q_{t-2}). \quad (1h)$$

Equations (1f), (1g) and (1h) bridge the theoretical and the empirical moments of the first difference of prices. These moments characterise the evolution of prices. In essay (3), I study the evolution of prices by building on the exposition of eq. (1c). However, in essay (3) I define the process of q_t as a complex process involving the duration of the trade and the size of the trade. Hence, the evolution of prices is affected by the arrival of traders, which can be measured in terms of the durations of trades, and the market thickness. Theoretically, the quantity and the direction of the trade play an important role in the realisation of the final value of a financial asset. For example, the Easley and O'Hara (1987) model predicts that an agent with superior information, as she is buying or selling, maximises her profit by trading in the largest possible size. Further, Garman (1976) shows that the arrival intensities for traders is a function of prices, thus the durations of trading events can be associated with the evolution of prices. Therefore, in the body of this dissertation, I define the arrival intensities as the difference in seconds between two successive transactions.

3.3 The Random Walk in the Short-Run

The microstructure theory deals with the birth and the formation of prices. However, the link between the microstructure theory and the random-walk theory of prices is not direct since over short intervals trading mechanisms often induce transient effects. Hasbrouck (2002) demonstrates that microstructure prices contain, however, an implicit random walk component that can be related to the permanent component of the trade. A general representation of the price process is as following:

$$p_t = p_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \sigma^2), \quad (2)$$

where p_{t-1} incorporates all available information, ε_t is a forecast error uncorrelated with any information at time t , $[\Phi_t]$, thus $E[\varepsilon_t] = 0$, $E[\varepsilon_t^2] = \sigma_\varepsilon^2$ and $E[\varepsilon_t \varepsilon_{t-1}] = 0$. Equation (2) can be viewed in two different ways. First, equation (2) can be viewed as restrictive by considering equation (2) as a fully completed process at each point of time. Second, equation (2) can be viewed as general to the theory on prices by considering equation (2) as representing a sequential evolution of prices at each point of time. The second view fits the theory on microstructure prices that contain a transient and a permanent component. Hasbrouck (2002) represents the random walk of microstructure prices in the following manner:

$$m_t = m_{t-1} + v_t, \quad (3)$$

$$p_t = m_t + s_t, \quad (4)$$

where m_t denotes the (unobservable) efficient price following a random walk process, v_t is an error term that is defined as $E[v_t] = 0$, $E[v_t^2] = \sigma_v^2$, $E[v_t v_{t-1}] = 0$ and s_t is an error term that arises from the transient component of the microstructure price such as bid-ask bounce, discreteness, and inventory effects. Equation (3) and (4) represent two random walk processes containing each a component that is said to be integrated of order one, and another component that is said to possess covariance-stationary first-differences that captures the transient component of prices. It follows that the random-walk component of equation (3) and (4) is the one with a permanent impact on prices. Furthermore, by substituting equation (3) into equation (4), it appears that equation (4) supports two error terms, v_t and s_t , which can be correlated. In conclusion, equation (3) and (4) provide the two basic components of the random walk theory of microstructure prices with useful implications on the conditional volatility of financial returns and the conditional process of any other financial vector of information (Madhavan (2000)). In essay (1) and (2), I study the volatility patterns of price changes by building on equation (3) and (4).

4. The Essays: Insights and Contributions

This dissertation contains three essays. Each essay has been written as an independent study, therefore some of the essential issues can be to some extent overlapping. The main argumentation in the three essays is that transaction time mimics the volatility process of stock returns.

4.1 On ACD Models: A Study of Volatilities

The purpose of this essay is to investigate the conditional variance process of stock returns regarding especially the impact of the intensity of trade on the conditional variance. The intensity of trade is defined according to different duration measures constructed on the expected duration mean. Therefore, the essay examines separately the stochastic process of durations including economic variables and the stochastic process of stock returns variance including both duration measures and trading variables. The essay documents that the conditional variance is related to the sign of the shock, the magnitude of the shock, and the intensity of trade, and that short durations are generally associated with high volatility. This essay differs from other ACD studies in two different ways. First, the essay investigates the forecast curve of three different ACD models. Second, unlike Engle (2000) to which the essay is related, the essay utilizes an asymmetric GARCH model to capture both the effects of trading intensity, and leverage.

4.2 The Effects of Trading Volume on Stock Returns

This essay investigates the periodic information pattern for small, middle-size and large transactions, respectively. The originality of the essay is in that an information epoch is defined as trading volume-based durations capturing the time it takes traders to trade a certain volume quantity. Market microstructure theories suggest that large transactions are informative. Hence, the essay examines both the causal relationship between the time until a certain volume is traded and the stock return variance, and the relationship between the stock return and the flow of information by developing a simple structure model giving rise to measures of variance, revision and learning dynamics. The essay documents that the return and the variance are increasing in the size of the transaction.

4.3 The Role of Time in Price Discovery

In this essay, I investigate the role of trade durations in price discovery within a structural microstructure model describing the evolution of price in financial markets. The model decomposes the variance of the price change in a component due to public information (the random walk theory) and a component due to trading frictions and market imperfections (the market microstructure theory). The autoregressive structure of the model requires an empirical model with a complex lag and a rich information structure. Therefore, the vector autoregressive model of Hasbrouck (1991) is used, and extended by including a time factor. Thus, the model is alike the Dufour and Engle (2000) empirical model. However, the model differs from Dufour and Engle (2000) in that it provides a theoretical motivation to the use of time as a factor in describing the evolution of prices in the short-run. Furthermore, the model permits the derivation of implied economic measures relative to information asymmetry and the bid-ask spread. Interesting results emerge from the analysis of 20 stocks among the most traded in the HEX. First, a buy arriving after a long duration has a lower impact on prices than a buy arriving after a short duration. Second, time duration has a stronger information asymmetry component than volume; however, both duration and size have long-run impacts on prices. Third, the information asymmetry accounts for about 17% and 14% of the total trading cost of the thick and thin stocks, respectively. The implied bid-ask spread is about 0.36€ and 0.52€ for thick and thin stocks, respectively. Finally, it is important to note that the impulse responses show that thick stocks react more rapidly to information than thin stocks.

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