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I. Introduction

The empirical intraday literature has identified a common pattern in returns, variance, and volume across the trading day. Each measure attains its maximum value during the opening hour of trading, then falls monotonically until midday, and then increases monotonically through the close. This pattern is in the shape of a reverse J, although it is often referred to in the literature as U-shaped. In an attempt to explain the reverse-J intraday pattern, two competing theoretical frameworks have been developed.¹ One is based on the role of private information in trading behavior, while the other is based on trading stoppages. Because most financial markets have private information and regular trading stops, it has been dif-

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1. See Atkins and Basu (1995) for a summary of the empirical literature. For the empirical work in specific markets, see, e.g., Wood, McNish, and Ord (1985), Jain and Joh (1988), Lockwood and Linn (1990), Laux and Ng (1993), and Lee and Linn (1994).

The intraday literature suggests that returns, variances, and volume form an intraday reverse-J pattern. Two competing theories explain the observed patterns: private information about future security prices and trading stoppages. The Federal funds market allows a unique opportunity to study the causes of intraday patterns because private information common to most markets does not play a role in setting prices. We find reverse-J variance patterns while accounting for generalized autoregressive conditional heteroskedasticity (GARCH) model effects. Our results support trading stops as an explanation for the reverse-J pattern and suggest that private information is not a necessary condition for the observed pattern.

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difficult empirically to disentangle the competing hypotheses. However, it is our goal to disentangle the competing hypotheses with intraday tests of the Federal (Fed) funds market.

The explanations based on private information require different types of traders with different information sets about future prices. For example, in their theory for the reverse J, Admati and Pfleiderer (1988) define three types of traders: (1) nondiscretionary liquidity traders who must trade a particular position at a particular point in time, (2) discretionary liquidity traders who have the ability to choose the timing of their trades strategically under the restriction that they must trade a particular position within a given period of time, and (3) informed traders who are privately informed about an asset's future returns. Admati and Pfleiderer (1988) suggest that diverse private information causes trading clusters around the trading of privately informed traders, which offers an explanation for the observed reverse-J pattern.

Hong and Wang (2000) extend the literature on private information to explain why trading is clustered at the open and the close.² They show that, in a market with hedgers (allocational trades) and speculators (private information trades), time-varying hedging dominates the trading at the open and time-varying information asymmetries dominate the trading at the close, which creates the observed intraday patterns. Hong and Wang (2000) suggest that market closures are required to explain the observed intraday patterns in a market that necessarily includes private information.

However, Brock and Kleidon (1992) explain clustering at the open and close in a model that requires only that trading cease at some point. They do not consider private information about future stock prices in their model. Brock and Kleidon (1992) suggest that increased and less elastic demand to trade occurs at the open and close of trading for two reasons. First, information arrives during the overnight nontrading period that causes the end-of-the-day position to deviate from the optimal position, necessitating trading at the open. Second, in preparation for the overnight nontrading period, the optimal position at the close is different from the optimal position during trading hours, which necessitates trading at the close.

The difficulty in empirically disentangling the effects of private information and trading stops on the observed reverse-J patterns is that both are common to most financial markets. However, both effects are not present in the Fed funds markets. The unique institutional features of the Fed funds market create a persistent rate-change pattern, which means that if any private information exists (about future interest rates), it is exceedingly difficult to exploit. Therefore, private information does not play a role in the rate-generating process in the Fed funds market. Thus, the Fed funds market provides a tightly defined experimental setting in terms of the competing hypotheses.

2. Slezak (1994) also suggests that market closures cause trading to cluster at the open and close in markets with private information. However, we focus on Hong and Wang (2000) because their model is more general.

Using hourly Fed funds rate changes in conditional variance models, we find evidence consistent with a reverse-J pattern for intraday volatility. We also find that the largest intraday rate changes are at the open and close of trading. However, because of the rules and regulations governing Fed funds, rates normally decline at the close but often increase at the open, so the intraday pattern does not form a reverse J.³ Our results suggest that private information is not a necessary condition for the reverse-J pattern. Instead, our findings suggest that overnight information flows and periodic market trading stops are sufficient to create the reverse-J pattern.

The article proceeds as follows: Section II discusses the institutional details of the Fed funds market and relates these details to the two competing hypotheses for the reverse-J pattern. Section III describes the data and presents our methods for the analysis. Section IV presents the results, while Section V concludes the article by discussing the implications of our findings.

II. The Fed Funds Market: Institutional Details, Models, Empirical Findings, and Implications for the Reverse-J Pattern

This section provides a thorough discussion of the Fed funds market to show the unique characteristics that make the market ideal for disentangling the competing hypotheses for the observed reverse-J pattern. The purpose is to provide the reader a clear understanding of (1) how this market functions, (2) the models of the market, (3) the previous empirical findings, and (4) how the Fed funds market relates to the existing explanations for the reverse-J pattern. Section II draws heavily from Spindt and Hoffmeister (1988), Griffiths and Winters (1995, 1997), Hamilton (1996), and Regulation D of the Code of Federal Regulations (1993). Specific cites will be made when appropriate.

A. Institutional Details

Banks are required by the Federal Reserve to hold a level of reserves (actual balances) based on a percentage of their deposits (required reserves). On a biweekly basis, banks must reconcile their actual reserves to their required reserves. The reconciliation process is referred to as settlement with the Federal Reserve. The 2-week period is referred to as a reserve maintenance period. A maintenance period includes 14 calendar days and normally includes 10 trading days. For each of the 14 calendar days, a bank has actual and required reserves. The actual and required reserves are based solely on end-of-day positions, and nontrading days are assigned the positions from the preceding trading day. The 14 end-of-day positions for both actual and required reserves are accumulated and compared for settlement. Since actual and required reserves rarely match exactly, successful settlement is achieved when the bank meets two requirements: (1) total actual reserves within a 4% range around

3. We do not have access to intraday volume data for the broker market for Fed funds and know of no source for intraday volume in this market.

their total required reserves and (2) alternating by maintenance period between settling with excess reserve (actual reserve $>$ required reserves) and short reserves (actual reserves $<$ required reserves).⁴ When a bank has successfully settled with the Federal Reserve, any deviation between actual and required reserves is carried forward as the starting position for the next maintenance period (Griffiths and Winters 1995).

As part of managing their actual reserves for successful settlement, banks trade reserves. The trades are Fed funds transactions. The primary reason for the trading of Fed funds is the management of reserves to achieve successful settlement with the Federal Reserve. In effect, banks that are deficient in their reserve accounts must trade regardless of the borrowing rate, and those with excess reserves have an incentive to trade at any positive rate once the required reserves plus maximum amount to carry over to the next period are met. Because all traders have 2 weeks in which to trade to achieve successful settlement with the Federal Reserve, they match the Admati and Pfleiderer (1988) definition for discretionary liquidity traders.

The Fed funds market is a market for interbank loans. Because it is a loan market, the parties to a Fed funds trade require a loan agreement. Since a loan agreement is required, banks maintain open lines of credit with other banks to facilitate trading. Thus, a trade in the brokered Fed funds markets requires (1) a standing loan agreement with the counter-party in the trade and (2) sufficient credit available under the loan agreement to accommodate the size of trade desired. Thus, the Fed funds market does not have specialists with private information about order flow making a market that could profit from strategic behavior.

Successful settlement with the Federal Reserve is the primary focus of a bank's reserve account management. Thus, based on the settlement rules, the end-of-the-day actual balance is the primary target in reserve account management. Banks track their reserve balances continually throughout the day; however, the balance they track to the end of the day is an estimate because of issues related to the clearing process. Banks are notified by the Federal Reserve of their actual end-of-the-day balance prior to the open of trading the next day. This feature of the Fed funds market is similar to equity market information arrival when the market is closed.

B. Fed Fund Market Models

Spindt and Hoffmeister (1988) developed a model of the daily and intraday variances in the Fed funds market. Their model focuses on the end-of-the-day accounting rules for settlement and shows that the periodic accounting for reserve balances creates predictable patterns in the variance. Spindt and Hoffmeister (1988) predict that (1) daily variances are heteroskedastic; (2) daily variances increase as settlement approaches, with settlement Wednesday

4. When a bank settles with the Federal Reserve, with actual reserves = required reserves, the bank can be either long or short in the next reserve maintenance period.

having the largest daily variance; and (3) afternoon variances are larger than morning variances. They do not include overnight factors in their model.

Griffiths and Winters (1995) extend the Spindt and Hoffmeister (1988) model to examine daily rate changes. Griffiths and Winters's (1995) model of daily rate changes is based on the asymmetry of the possible settlement positions and the end-of-the-day accounting rules. They show that settling with excess reserves is a lost investment opportunity while settling with a short reserve position is an extra investment using an interest-free loan from the Federal Reserve. Based on the asymmetric positions, Griffiths and Winters (1995) predict daily rate changes as follows: (1) rates decline in general across the settlement period, (2) rates decline on Fridays, (3) rates decline on the second Tuesday (the day before settlement), and (4) rates increase on settlement Wednesday.⁵ The model is based on end-of-the-day positions and thus does not make intraday predictions.

C. Previous Empirical Results in Fed Funds

The empirical results for daily and intraday variances in the Fed funds market are as follows: Spindt and Hoffmeister (1988), using Parkinson's (1980) extreme-value method variance estimator with daily high and low rates, find that daily variances are heteroskedastic, with settlement Wednesday having the largest daily variance. Griffiths and Winters (1995), using daily high and low rates, verify the findings of Spindt and Hoffmeister (1988). In addition, using morning and afternoon high and low rates, Griffiths and Winters (1995) find that afternoon variances are higher than morning variances. Using closing rates, Griffiths and Winters (1997) find results consistent with previous studies for daily variances in Fed funds and overnight government repos.⁶ Cyree and Winters (2001) use hourly Fed funds rates in conditional variance models and find that, on average, overnight and afternoon variances add to the conditional variance. Cyree and Winters also find strong autoregressive conditional heteroskedasticity (ARCH) and generalized autoregressive conditional heteroskedasticity (GARCH) effects in the variance equation, which suggests that intraday studies of the Fed funds market should control for these effects.

The empirical results on rate changes under the current biweekly reserve maintenance period start with Saunders and Urich (1988). They find that rates generally decline across the 2-week maintenance period. Griffiths and Winters (1995), using daily high and low rates, find that rates (1) decline on Fridays, (2) decline on the second Tuesday (the day before settlement), and (3) increase

5. Each reserve maintenance period covers 2 weeks, so each maintenance period has two Mondays, two Tuesdays, etc. Because the models of the Fed funds market make predictions for specific days of the maintenance period, the standard convention in the Fed funds literature is to identify the days with their week and day reference, such as first Tuesday. The one exception is the second Wednesday, which is referred to as settlement Wednesday to denote the end of the reserve maintenance period and settlement with the Federal Reserve.

6. Griffiths and Winters (1997) discuss overnight government repos as a substitute asset for Federal Reserve settlement and show that the patterns created by the settlement rules spill over into the market for the substitute asset.

on settlement Wednesday. Hamilton (1996) finds the same rate-change pattern as do Griffiths and Winters (1995) in the effective Fed funds rate. The effective Fed funds rate is a transaction-weighted daily average. From these results, Hamilton (1996) concludes that rate changes do not follow a Martingale process and, thus, that banks do not view reserves on different days as perfect substitutes. Griffiths and Winters (1997) also find the same rate-change pattern in overnight government repo rates, which is a substitute asset for Fed funds in settlement with the Federal Reserve. Cyree and Winters (2001) find the same rate-change pattern using closing rates in conditional variance models with no evidence of volatility-in-mean effects. Cyree and Winters extend their analysis to hourly rates in conditional variance models with dummy variables for the overnight (close to open) and afternoon (noon to close) time periods, and they find results similar to their results using closing rates.

D. The Reverse-J Pattern

In this section, we present the primary features of the competing hypotheses and how these features relate to the Fed funds market. We begin with the features of the private information theories and then discuss the features of trading stoppages.

Private information. Private information is defined as information about future securities prices. If private information is exploitable and thus affects security prices, then the market must have different types of traders. Admati and Pfleiderer (1988) suggest three trader types and discuss how the strategic behavior of the different trader types creates trading clusters.⁷ In Section IID, we discuss the trader types apparent in the Fed funds market and the role of private information.

Each reserve maintenance period is 2 weeks long, but at the end of the 2-week period, each bank must settle its reserve account position with the Federal Reserve. Since the banks must settle but have some discretion on when they trade to achieve settlement, the banks are discretionary liquidity traders under the trader types defined by Admati and Pfleiderer (1988). Discretionary liquidity traders have the ability to time their trades strategically and therefore have the opportunity to exploit private information. However, in the Fed funds market, if private information about future interest rates (security prices in this market) exists, it is exceedingly difficult to exploit.

The existing empirical work on the Fed funds market shows a persistent pattern in rate changes. A persistent pattern in any market provides a profitable opportunity to informed traders unless other market features dominate the apparent profits from trading on the pattern. The pattern in the Fed funds market is consistent with the incentives created by the rules and regulations governing the settlement process with the Federal Reserve. Thus, it appears

7. Hong and Wang (2000) suggest two different trader types: hedgers and speculators. However, we chose to use the three trader types from Admati and Pfleiderer (1988) in our discussions of trader types.

that successful settlement with the Federal Reserve dominates profitable trading opportunities as the primary trading objective. In addition, Brown et al. (1999) identify a profitable trading strategy in the Fed funds market that persists. They suggest that the profitability of the trading strategy persists because the need to settle with the Federal Reserve dominates any risky profitable trading strategy. Accordingly, we conclude that private information does not have a role in setting interest rates (prices) in this market.

Even with a rate-change pattern consistent with the incentives created by the settlement rules and regulations, there may be a concern about the lack of a role for private information given the correspondent relationship between large and small banks in the Fed funds market. Small banks typically lend their excess reserves to their correspondent bank, which could provide the correspondent banks with private information about available reserves. We remove the role of correspondent relationships in rate setting by using only data from the broker market for Fed funds. Stigum (1990) notes that the broker market is for the top 500 U.S. banks plus some foreign banks.

For the banks that regularly trade in the brokered Fed funds market, there may be concern about private information about customer cash flows. Spindt and Hoffmeister (1988) model the customer cash flows through a bank's reserve account as stochastic, and our discussions about intraday reserve account cash flows with Fed funds traders support describing these cash flows as stochastic cash flows. The traders indicate that some cash flows are predictable, but they are industry-wide cash flows such as social security checks. Accordingly, we do not believe a set of better-informed traders exists in the brokered Fed funds market.

There remains one trader affecting the Fed funds market that may act as an informed trader in the Fed funds market. That trader is the open market desk. The open market desk regularly trades short-term government repos with the policy objective of attaining the target Fed funds rate. If the open market trading desk is an informed trader trading on private information, then the theory developed by Admati and Pfleiderer (1988) suggests that trading will cluster around the trading of the open market desk. Open market desk trading has the unique feature that it occurs one time each day: the timing of the trading is always in the late morning. Thus, if the open market desk is an informed trader trading on private information, then we would expect to find high intraday rate changes and volatility in the late morning in the Fed funds market. We know of no prior research on intraday Fed funds market behavior around open market desk trading. We will present our intraday results hourly and will discuss the results from late in the morning as they relate to the informed trader role of the open market desk.

Finally, some of the work on private information has examined the role of market specialists. For example, Stoll and Whaley (1990) suggest that the high volatility at the open is from the strategic behavior of the market specialist using the private information available to that specialist. However, Ekman (1992) and Sheikh and Ronn (1994) find U-shaped intraday patterns in markets

without specialists. Accordingly, the presence of a market specialist may be a sufficient condition for the reverse-J intraday pattern, but it is not a necessary condition. The brokered market for Fed funds does not have a market specialist.

Trading stoppages. Brock and Kleidon (1992) suggest that in preparation for the overnight nontrading period, the optimal position at the close is different from the optimal position during trading hours. Their findings suggest that trading stoppages cause the need to trade at the close of daily trading. In Fed funds, settlement with the Federal Reserve is based only on a bank's reserve position at the close of each trading day. Spindt and Hoffmeister (1988) base their model on the end-of-the-day accounting system and predict higher intraday variance at the close, as banks more aggressively trade at the end of the day to offset deviations from their end-of-the-day target reserve balance.

In addition, Brock and Kleidon (1992) suggest that information arrives during the nontrading period that causes the end-of-the-day position to deviate from the optimal position, which causes a need to trade at the open. In the Fed funds market, the end-of-the-day actual reserve position is an estimate. Prior to the next day's open, the Federal Reserve notifies each bank of any change in its end-of-the-day estimate to arrive at its actual closing position. Thus, new information arrives overnight that may require banks to trade at the open to achieve its desired position.

In summary, the institutional features of the Fed funds market fit closely with the primary features of the Brock and Kleidon (1992) model, which is based on trading stoppages. In addition, the Fed funds market provides a rare opportunity to isolate and test the effects of trading stoppages on trading behavior because private information about future returns does not play a role in the rate-generating process.

III. Data and Methods

A. Data

Our data are intraday Fed funds rates collected from the daily logs of the International Monetary Market Division of the Chicago Mercantile Exchange. The International Monetary Market purchases the data from Telerate Corporation, which acquires the data from the Federal Reserve Bank of New York. We have the following intraday rates: (1) hourly rates from 9:00 A.M. to 3:00 P.M. Eastern time and (2) the closing rate (6:30). The Fed funds broker market opens at 8:30 A.M., so our first daily rate observation (9:00 A.M.) is a half hour after the open of trading. The rates are bid-side broker quotes. Having only bid-side quotes removes any possible problems related to switching between bid and ask prices. The data cover the period from February 2, 1984, to January 31, 1996. The beginning of the period coincides with the Federal Reserve's switch to biweekly settlement.

TABLE 1 Descriptive Statistics for the Hourly Fed Funds Rates

	Mean	Median	SD	Max	Min	Range
Panel A, Hourly Average Rates						
9:00 A.M.	6.53	6.56	2.19	11.94	2.81	9.13
10:00 A.M.	6.54	6.56	2.19	12.50	2.81	9.69
11:00 A.M.	6.54	6.56	2.20	12.50	2.81	9.69
12:00 P.M.	6.54	6.56	2.20	12.50	2.75	9.75
1:00 P.M.	6.54	6.56	2.20	12.50	2.63	9.87
2:00 P.M.	6.54	6.56	2.20	12.25	2.63	9.63
3:00 P.M.	6.55	6.56	2.20	12.50	2.00	10.50
Close	6.50	6.50	2.23	13.00	1.00	12.00
Panel B, Rate Change by Observation						
9:00 A.M.	.024	.00	.40	5.12	-5.69	10.81
10:00 A.M.	.002	.00	.07	1.00	-1.00	2.00
11:00 A.M.	.002	.00	.06	1.00	-1.00	2.00
12:00 P.M.	-.004	.00	.07	1.06	-.63	1.69
1:00 P.M.	-.005	.00	.10	1.38	-2.25	3.63
2:00 P.M.	-.003	.00	.10	1.00	-2.00	3.00
3:00 P.M.	.001	.00	.15	3.00	-2.50	5.50
Close	-.019	.00	.29	3.50	-3.50	7.00

NOTE.—The rates are (1) hourly from 9:00 A.M. to 3:00 P.M. Eastern standard time and (2) at the close (6:30 P.M.). The daily open of trading is at 8:30 A.M. The sample period covers from February 2, 1984, to January 31, 1996. All numbers are presented as percentages. Max = maximum; min = minimum.

Table 1 provides some summary statistics. Panel A provides statistics on rates at each of our intraday sampling points. Panel B presents statistics for rate changes between each of our intraday sampling points. Panel A shows that the average rate is surprisingly similar across the intraday sampling points. The statistics do hint at the variance increasing toward the end of the day. Panel B shows that the largest rate changes occur at the close and overnight. The declining rates at the close are consistent with the incentive to run a short position in reserves, as discussed in Griffiths and Winters (1995). The standard deviations and ranges show a reverse-J pattern for intraday volatility. However, we need to emphasize that these are preliminary results for two reasons. First, these are average results across the time series. To support an intraday pattern properly, we must show that the pattern exists on each trading day. Accordingly, we will examine separately each of the 10 trading days of the reserve maintenance period for evidence of a reverse-J pattern. Second, Cyree and Winters (2001), using a time series of hourly rates, find ARCH, GARCH, and asymmetric effects in the conditional variance. Thus, as we examine each trading day, we must control for conditional variance effects properly to isolate intraday changes related to the time of the day.

B. Methods

We use a GARCH model with the conditional variance equation, as proposed by Glosten, Jagannathan, and Runkle (1993), with a modification from Hamilton (1996). We selected the Glosten et al. (1993) variance model because of its definition of the asymmetric term in the conditional variance; we then

modified the variance model to subtract the expected value at time t , as in Hamilton (1996).⁸ This conditional variance model contains an intercept and three prespecified variables in the variance equation: (1) a trend term (referred to as an ARCH effect), (2) a persistence term (a GARCH effect), and (3) a sign of the error term (an asymmetric effect). The asymmetric term allows that certain errors are more important to the market than other errors and conditions the variance based on the sign of the error term. The Glosten et al. (1993) asymmetric term is a binary dummy variable that we feel is intuitively appealing for the Fed funds market.

The Glosten et al. (1993) model is a specific application of a GARCH model (as originally proposed by Engle [1982] and generalized by Bollerslev [1986]) that, by design, accounts for the time-varying variance. The Glosten et al. (1993) model's mean equation for day j of the reserve maintenance period is⁹

$$R_t - R_{t-1} = \beta_9 D_9 + \beta_{10} D_{10} + \beta_{11} D_{11} + \beta_{12} D_{12} + \beta_{13} D_{13} + \beta_{14} D_{14} + \beta_{15} D_{15} + \beta_{\text{close}} D_{\text{close}} + \varepsilon_t, \quad (1)$$

where

R_t = the Fed funds rate at time t during day j ,¹⁰

D_i = 0/1 dummy variable, $D_9 = 1$ for the overnight time period from the close to 9:00 A.M. and 0 otherwise, $D_{\text{close}} = 1$ for the trading period at the close and 0 otherwise, $D_{10} = 1$ for the trading period from 9:00 A.M. to 10:00 A.M. and 0 otherwise, with $D_{11} - D_{15}$ defined in a similar manner for the hours from 11:00 A.M. to 3:00 P.M. Eastern time,

ε_t = the error term, which is assumed to be normally distributed.

The Glosten et al. (1993) model accounts for asymmetric variance effects in the conditional variance equation. The conditional variance equation for the Glosten et al. (1993) model on day j is

$$\sigma_t^2 - \kappa_t = \alpha_0 + \alpha_1(\varepsilon_{t-1}^2 - \kappa_{t-1}) + \alpha_2(\sigma_{t-1}^2 - \kappa_{t-1}) + \alpha_3(\varepsilon_{t-1}^2 - \kappa_{t-1})I_t, \quad (2)$$

where

8. We also tested two other specifications of GARCH to ensure that our results were not an artifact of our model choice. The other models are the EGARCH specification suggested by Nelson (1991) with two different specifications of the error term in the mean equation: (1) normal distribution of errors and (2) GED distribution of errors. The results from these specifications are qualitatively similar to the results reported. They are not reported for brevity but are available on request.

9. There are 10 trading days in a reserve maintenance period, so j varies from 1 to 10. We estimate the model separately for each trading day, so j is not included in the model notation. Glosten et al. (1993) use nonstandard notation in their GARCH model. We chose to present our model using standard notation (see, e.g., Chou, Engle, and Kane 1992), with the addition of the Glosten et al. (1993) asymmetric term in the conditional variance equation.

10. We note that Fed funds trade at face value with interest paid separately. This means that the Fed funds rate is the price of the instrument. Thus, our first difference in Fed funds rates is a standard return calculation.

$$\begin{aligned} \kappa_t = & \gamma_9 D_9 + \gamma_{10} D_{10} + \gamma_{11} D_{11} + \gamma_{12} D_{12} + \gamma_{13} D_{13} \\ & + \gamma_{14} D_{14} + \gamma_{15} D_{15} + \gamma_{\text{close}} D_{\text{close}} \end{aligned} \quad (3)$$

and I_t = a dummy variable equal to 1 if the lagged error is negative and 0 otherwise. The indicator variable accounts for asymmetry in the conditional variance equation as the addition to variance based on the sign of last period's error.

The dummy variables in equation (3) are as defined above for equation (1). The model is estimated by maximum likelihood. The subtraction of κ_t is similar to Hamilton (1996) and models the variance in terms of the deviations from the unconditional expectation κ_t for each period.¹¹ If we did not write the model in terms of deviations from the unconditional expectation, the systematic changes over the day would be obscured by the GARCH dynamics; for example, if $\tilde{\gamma}_9 \neq \tilde{\gamma}_{10}$, the difference would be carried over into the next period through the lagged variance term. The ARCH, GARCH, and asymmetric terms represent these effects over and above the expected value of the variance, given we are at hour t . In this manner, the coefficients on the dummies in the variance equation represent the expected incremental change in variance for hour t , and the other GARCH effects incorporate these expectations.

Equation (1) is the mean equation for the GARCH model and includes a 0/1 dummy variable for each of the trading hours during a reserve maintenance period day. We keep all the dummy variables and omit an intercept so that the independent variables will not be linearly dependent. This specification allows us to retain the information about each observation during a trading day. Equation (2) is the variance equation and includes all hourly dummy variables from equation (3) and an intercept. This is appropriate in the conditional variance equation of a GARCH model because the intercept represents the unconditional variance and the other variables represent conditioning effects.¹²

We estimate the model for each of the 10 trading days of the reserve maintenance period.¹³ Estimating the model separately for each of the 10 trading days is very important for addressing the theories for the reverse-J pattern. To identify a regular intraday pattern, one must show that the pattern

11. Note that Hamilton's (1996) definition is for daily effects, whereas our variable represents hourly effects. We thank an anonymous referee for suggesting this specification to avoid a self-imposed systematic pattern.

12. We note that the GARCH literature often assumes the presence of ARCH and GARCH effects. Under this assumption the intercept is not the unconditional variance. However, if one does not presuppose the existence of ARCH, GARCH, or hourly effects, then the intercept is the unconditional variance.

13. With a sample period from February 2, 1984, to January 31, 1996, we have approximately 300 observations for each intraday sampling point for each day for all trading days except Mondays. Mondays have approximately 270 observations at each intraday sampling period. The lower number of observations on Mondays results from the concentration of nontrading holidays on Monday. The actual number of observations varies slightly because of a few missing observations and a few trading days that close early.

dominates across the different trading days of the market being studied. For most markets, this means finding the pattern on each day of the week (Jain and Joh 1988; McInish and Wood 1992). However, because the Fed funds market operates on 2-week cycles, this means finding the pattern on each of the 10 trading days of the reserve maintenance period. Examining each day separately is particularly important in the Fed funds market because certain days have unique trading pressures related to the reserve maintenance process.

Previously, Griffiths and Winters (1995) and Cyree and Winters (2001) have shown that, on average, afternoon variances are larger than morning variances, and Cyree and Winters have shown that, on average, overnight variances are higher than morning variances. These results hint at the presence of a reverse-J pattern. However, these studies do not show whether these results are common to each day of the reserve maintenance period or are the result of a few unique days. In addition, both studies define the morning to cover the time period from the market open until noon and the afternoon to cover the time period from noon to market close at 6:30 P.M. Accordingly, these studies provide no insight into the shape of the hourly pattern across the day.

IV. Results

Tables 2 and 3 present the results from estimating the conditional mean and conditional variance models for each of the 10 trading days of the reserve maintenance period. Table 2 presents the mean equation results, and table 3 presents the conditional variance results. In Section IV, we first discuss the results in the mean equation to verify prior research and the validity of our model. We next discuss the intraday variance results to see if there is support for the reverse-J pattern in volatility in a market where private information does not play a role in setting prices.

A. *Intraday Conditional Mean Rate-Change Results*

The incentives created by the rules of the Fed funds market suggest that rates should decline at the end of the day (except for settlement Wednesday) because it is an advantage to all banks to maintain actual reserve positions that are less than their required reserve positions. Following the end-of-the-day pressures, we expect rates to rebound at the open. Thus, intraday rate changes should not form a reverse-J pattern. However, the mean equation results are interesting for two reasons. First, we verify that our results are consistent with prior research and not unique to our model and data. Second, we show that the largest intraday rate pressures are at the open and close of the trading day.

Table 2 reports the results from the mean equation for the Glosten et al. (1993) model by the trading day of the reserve maintenance period. We find that, in absolute value terms, the overnight rate change is the largest rate

TABLE 2 Mean Equation Results (Glosten et al. Model)

Estimates	First Week of the 2-Week Reserve Maintenance Period					Second Week of the 2-Week Reserve Maintenance Period				
	First Thursday	First Friday	First Monday	First Tuesday	First Wednesday	Second Thursday	Second Friday	Second Monday	Second Tuesday	Second Wednesday
β_9	-.02110 (-1.530)	-.11409** -10.344 (.344)	.07943** (56.314)	-.00106 (-1.46)	.02859* (1.976)	.03315 (-1.527)	.04890** (9.214)	.0625** (13.736)	.01189 (1.595)	-.06250** (-21.597)
β_{10}	-.00013 (-.038)	.00324 (.344)	-.00876** (5.009)	-.00064 (-.031)	.00441 (2.54)	.03583 (1.107)	-.00279 (-1.026)	.0090* (2.214)	.00676 (.364)	.01669* (2.481)
β_{11}	.00329 (1.760)	.01233 (.669)	-.00541** (2.848)	-.00702 (-1.089)	-.00457 (-1.109)	-.00065 (-.012)	.00033 (.137)	.0001 (.041)	.00212 (.951)	.00414 (.757)
β_{12}	.00123 (.502)	.01183 (.615)	-.00259 (-1.374)	.00572 (.100)	-.01047 (-4.16)	.04079 (.825)	-.01074** (-3.312)	.0029 (1.229)	-.00406 (-1.195)	-.01075 (-1.570)
β_{13}	.00510 (1.227)	.00290 (.239)	-.00163 (-4.98)	-.00768** (-3.380)	-.00804 (-1.86)	-.03337 (-9.949)	-.00375 (-1.611)	-.0006 (-.252)	.00880* (-2.640)	.00345 (.568)
β_{14}	.00510* (2.029)	-.00473 (-.393)	-.00396** (-11.584)	-.00779** (-2.984)	.00772 (.392)	-.03430 (-8.77)	-.00218 (-1.068)	-.0052* (-2.148)	-.01537** (-3.121)	.01983** (3.094)
β_{15}	.00982* (2.385)	-.02494 (-1.425)	-.01123 (-1.363)	-.00816** (-2.800)	.00726 (.465)	-.00274 (-.099)	.00143 (.434)	.0047 (1.130)	-.02813** (-3.325)	.04653** (10.602)
β_{close}	.01826 (.881)	-.01233 (-.890)	-.01090** (-5.565)	-.03356** (-4.131)	-.00661 (-4.21)	-.06413* (-2.101)	-.03955** (-9.303)	.0138** (-3.957)	-.09322** (-11.918)	.07249** (12.468)

NOTE.—The Glosten et al. (1993) mean equation results are for the 1984–96 sample of hourly Fed funds rates by reserve maintenance period day. The return equation modeled using R_t is the hourly Fed funds rate change at time t on day j , which is

$$R_t - R_{t-1} = \beta_9 D_9 + \beta_{10} D_{10} + \beta_{11} D_{11} + \beta_{12} D_{12} + \beta_{13} D_{13} + \beta_{14} D_{14} + \beta_{15} D_{15} + \beta_{close} D_{close} + \epsilon_t$$

where the D_j represent dummies for each hour of the trading day. The errors are assumed normally distributed, and t -statistics are beneath the coefficients in parentheses.

* Significant at the 5% level.
** Significant at the 1% level.

TABLE 3 Variance Equation Results (Glosten et al. Model)

Estimates	First Week of the 2-Week Reserve Maintenance Period							Second Week of the 2-Week Reserve Maintenance Period							
	First Thursday	First Friday	First Monday	First Tuesday	First Wednesday	First Thursday	First Friday	Second Monday	Second Tuesday	Second Wednesday	Second Thursday	Second Friday	Second Monday	Second Tuesday	Second Wednesday
α_0	.0315 (3.822)	.02348** (8.283)	.00536** (106.283)	-.00998** (-3.224)	.00125 (.261)	.05085 (1.214)	-.00090* (-2.046)	.0116** (11.088)	.00572** (8.549)	.01268** (28.725)					
α_1	.0613 (21.511)	.14048** (7.584)	.36654** (40.425)	.16328** (15.540)	.15288** (5.109)	.03818** (11.071)	.31097** (26.797)	.2700** (28.999)	.26891** (22.164)	.17261** (28.784)					
α_2	-.0017 (-6.843)	.52931** (19.628)	.27104** (197.861)	.19135** (10.480)	.23606** (3.778)	.58906** (18.636)	.54148** (81.216)	.1596** (32.606)	.24255** (36.907)	.47190** (74.817)					
α_3	-.0078 (-5.080)	.01812 (1.061)	.01931 (1.523)	-.04529** (-3.366)	.01028 (.501)	-.00530 (-1.842)	.01637** (3.938)	.0865** (10.277)	.00321 (.220)	-.29266** (-50.749)					
γ_9	.1765 (19.234)	-.01143 (-1.166)	.01967* (36.843)	.04749** (10.546)	.04695** (5.752)	-.04356 (-1.383)	.06056** (19.360)	.02779** (16.922)	.02424** (15.585)	.02529* (25.649)					
γ_{10}	-.0196 (-2.270)	-.06098** (-6.428)	-.00299** (-9.507)	.01352** (2.831)	.023630** (2.909)	-.09403 (-1.798)	.03181** (10.232)	.0054** (2.937)	-.01736** (-34.280)	-.00025 (-.587)					
γ_{11}	-.03193* (-3.643)	-.05747** (-5.439)	-.00641** (-29.655)	.01523** (3.338)	.00540 (.709)	-.09737 (-1.854)	.02809** (9.057)	-.0141** (-7.289)	-.00952** (-17.624)	-.00690** (-13.646)					
γ_{12}	-.03139** (-3.598)	-.04761** (-4.947)	-.00401** (-12.202)	.01921* (2.210)	.01879* (2.356)	-.08695 (-1.759)	.02772* (9.013)	-.0175** (-9.016)	-.00903** (-9.673)	-.00709** (-11.721)					
γ_{13}	-.02987** (-3.420)	-.05659** (-5.864)	.00387** (346.057)	.01908** (3.886)	.03086** (3.581)	-.09098 (-1.798)	.02393* (7.653)	-.0187** (-9.649)	-.00863** (-7.699)	-.00518** (-6.221)					

γ_{14}	-.0312 (-3.584)	-.05869** (-6.115)	-.00664** (-81.592)	.01785** (4.072)	.01706* (2.092)	-.07315 (-.640)	.02138* (6.935)	-.0188** (-9.826)	-.00667** (-5.347)	-.00109 (-1.306)
γ_{15}	-.0292 (-3.351)	-.04976** (-4.969)	-.00199** (-4.675)	.01798** (4.110)	.01736* (2.180)	-.08645 (-.757)	.02111* (6.880)	-.0122** (-6.388)	.00089 (.668)	.05435** (68.354)
γ_{close}	.01856* (2.102)	-.03494** (-3.519)	.00679** (12.375)	.03237** (7.361)	.04561* (5.273)	-.05617 (-.492)	.02941** (9.611)	.0017 (.786)	.04423** (23.165)	.27533** (61.853)

NOTE.—The Glosten et al. (1993) variance equation results are for the 1984–96 sample of hourly Fed funds rates by reserve maintenance period day. The variance is

$$\sigma_t^2 - \kappa_t = \alpha_0 + \alpha_1(\varepsilon_{t-1}^2) + \alpha_2(\sigma_{t-1}^2 - \kappa_{t-1}) + \alpha_3(\varepsilon_{t-1}^2 - \kappa_{t-1})V_t$$

where $\kappa_t = \gamma_0 D_{t-9} + \gamma_{10} D_{t-10} + \gamma_{11} D_{t-11} + \gamma_{12} D_{t-12} + \gamma_{13} D_{t-13} + \gamma_{14} D_{t-14} + \gamma_{15} D_{t-15} + \gamma_{close} + D_{close}$ and I_t is a dummy equal to 1 if the prior error is negative and 0 otherwise. In all cases, the D_t represent dummies for each hour of the trading day. The errors are assumed normally distributed, and t -statistics are beneath the coefficients in parentheses.

* Significant at the 5% level.

** Significant at the 1% level.

change for 6 of 10 trading days and is the second largest rate change on one other day. We should note that the overnight rate change is from the close of the previous day to 9:00 A.M. of the current day, and since trading opens at 8:30 A.M., the overnight period includes the first half hour of the day's trading. The rate change at the close is the largest intraday rate change during 4 of the 10 trading days and is the second largest on another 3 days. This suggests that a general pattern exists, with the largest intraday rate changes occurring at the open and the close of trading. These patterns are generally consistent with existing intraday literature. The patterns in intraday rate changes are also consistent with the existing literature on daily Fed funds rate changes. Our model is on a day-by-day basis and confirms that the general effects are not because of a single day but generally appear across days in the reserve maintenance period.

B. Intraday Conditional Variance Results

Table 3 reports the Glosten et al. (1993) conditional variance parameter estimates. We find strong evidence of consistent ARCH and GARCH effects across the trading days. Specifically, we find significant at the 1% level and positive ARCH effects on all 10 trading days, and we find significant at the 1% level and positive GARCH effects for 9 of 10 trading days (the first Thursday is significant and negative). These results suggest that trends exist in the intraday variances (ARCH effects) and that intraday variances are persistent (GARCH effects).

For intraday variances, we are concerned with the incremental effect of each hour of the individual trading day, and the coefficients on the dummies in the variance equations capture these effects. Thus, if the intraday variance patterns are present in these coefficients, the effect is not because of (1) informed traders, (2) private information, (3) profit motives, or (4) GARCH effects.¹⁴ Therefore, reverse-J or similar patterns in Fed funds represent a direct test that intraday patterns are likely because of overnight information arrival that affects the beginning of trading and late-day positioning for the overnight nontrading period that influences the close.

The parameter estimates for intraday variances are reported in table 3 as $\gamma_9 - \gamma_{15}$ and γ_{close} , where γ_9 represents the overnight variance. The results show that the largest intraday variance occurs overnight for 8 of the 10 trading days.¹⁵ The overnight variance is the second largest intraday variance on

14. Hasbrouck (1999) examines intraday bid-ask spreads. He finds common cost components in the bid-ask spread and argues that these costs reflect risk as proxied for by the ARCH model variance.

15. Note that the each dummy variance provides the incremental effect on the conditional variance at time t . Accordingly, the largest intraday variance occurs with either the largest positive parameter or the least negative parameter, such as on the first Friday where the overnight parameter of -0.01143 is the least negative parameter during the day.

another trading day.¹⁶ The variance at the close has the largest intraday variance for 2 of the 10 trading days and the second largest variance on another 7 trading days. Interestingly, the overnight variance is largest for the first 8 trading days, while the variance at the close is largest for the last 2 trading days. Also, the trading day where the overnight variance is not one of the two largest intraday variances is settlement Wednesday, where the largest intraday variance is at the close and the second largest intraday variance is at 3:00 P.M.

Figure 1 plots the γ parameter estimates and contains 10 graphs, one for each of the 10 trading days of the reserve maintenance period. The graphs show a reverse-J pattern over the first 8 trading days of the reserve maintenance period and a J pattern over the last 2 trading days of the reserve maintenance period.¹⁷ These results suggest that the pattern of the largest intraday variances at the open and close of trading occurs across the days of the reserve maintenance period, and thus they are not the result of a few trading days. These results are consistent with the existing intraday literature.¹⁸

Finally, we note that we found no evidence of high intraday variance in the late morning hours, which suggests that Fed funds trading does not cluster around open market desk daily trading. This suggests either (1) that the open market desk is an exogenous factor to Fed funds rate behavior or (2) that the

16. A possible explanation for the high variance at the open for which we do not control is regular macroeconomic announcements. Christie-David and Chaudhry (1999) show that macroannouncements cause intraday variance spikes in interest-rate-based financial futures. They document that the first announcement of a day is at 7:30 A.M. Central time (the same time as the open of the Fed funds market) and that the variance spike occurs during the following 15-minute time interval. They also document that during their sample period (January 3, 1994–December 29, 1995) there were not any 7:30 A.M. announcements on Mondays. Based on the Christie-David and Chaudry (1999) results, we believe our results are not caused by macroeconomic announcements because our Monday variance pattern matches those of the other days of the week and they find no Monday 7:30 A.M. macroannouncements in their sample.

17. To verify further the shapes of the intraday variance graphs, we examine the 95% confidence intervals for the parameter estimates on each of the 10 trading days. We do not include the confidence intervals in fig. 1 because on 4 of the 10 trading days the confidence intervals were narrow enough to appear as a single line in our graphs. The reason for examining the confidence intervals is to determine if intraday patterns in shapes other than a J or a reverse J are possible within the confidence intervals. For 9 of the 10 trading days, intraday patterns other than a J or reverse J are not possible within the confidence interval. The one exception is the first Wednesday, where the confidence interval is wide enough to accommodate shapes that differ significantly from the shape of the graph for the first Wednesday in fig. 1.

18. It is well known that returns and variance across longer time intervals are expected to be greater than the returns and variance across shorter time intervals, *ceteris paribus*. Our largest intraday variances are from close to 9:00 A.M. and from 3:00 P.M. to close, which cover longer time intervals than our other intraday intervals. Thus, our results could be an artifact of our intraday data sampling points. To check for the problem of different time intervals, we scale the close–9:00 A.M. variance for each day and compare it to the 9:00 A.M.–10:00 A.M. variance for the same day; we also scale the 3:00 P.M.–close variance and compare it to the 2:00 P.M.–3:00 P.M. variance from the same day. Using a means difference test, we find that the scaled close–9:00 A.M. variance is significantly larger than the 9:00 A.M.–10:00 A.M. variance on 7 of the 10 trading days. We also find that the scaled 3:00 P.M.–close variance is significantly larger than the 2:00 P.M.–3:00 P.M. variance on the same 7 trading days. These results suggest that intraday J curve in Fed funds is not an artifact of the data sampling intervals.

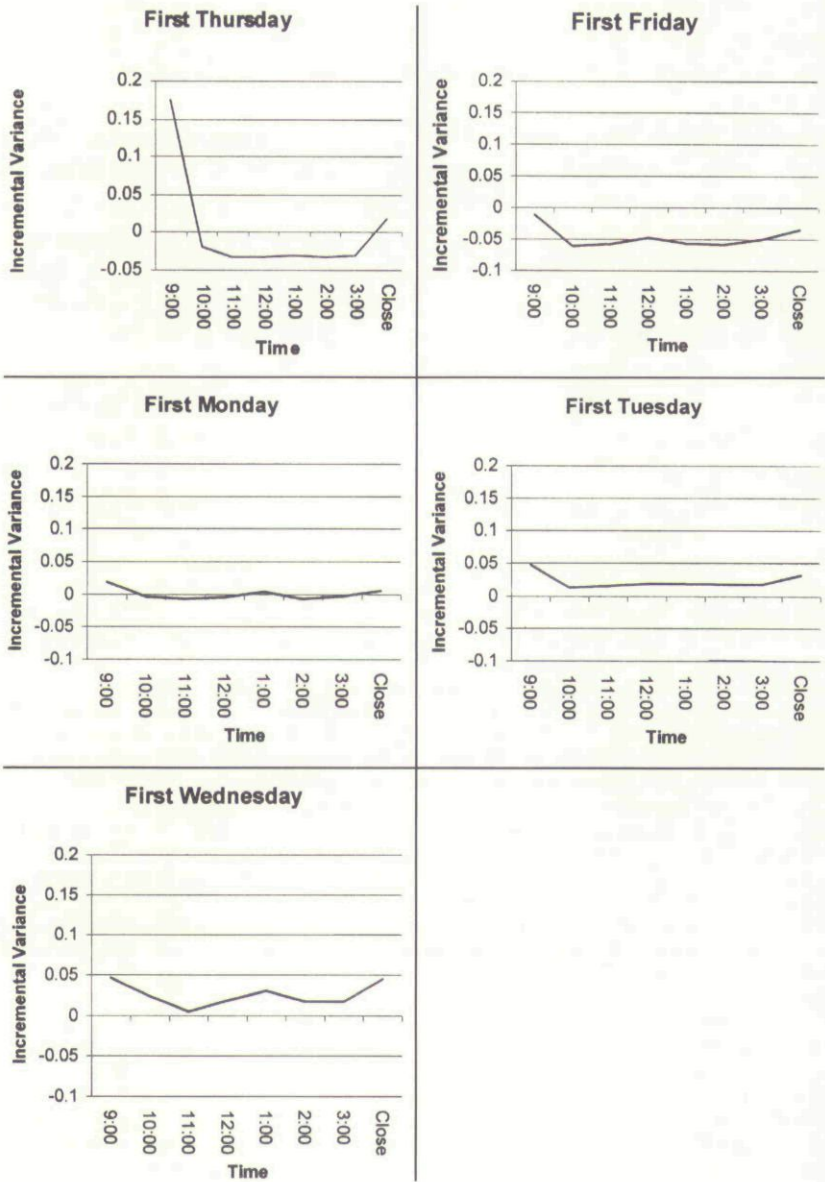


FIG. 1.—Incremental variance by day of the reserve maintenance period

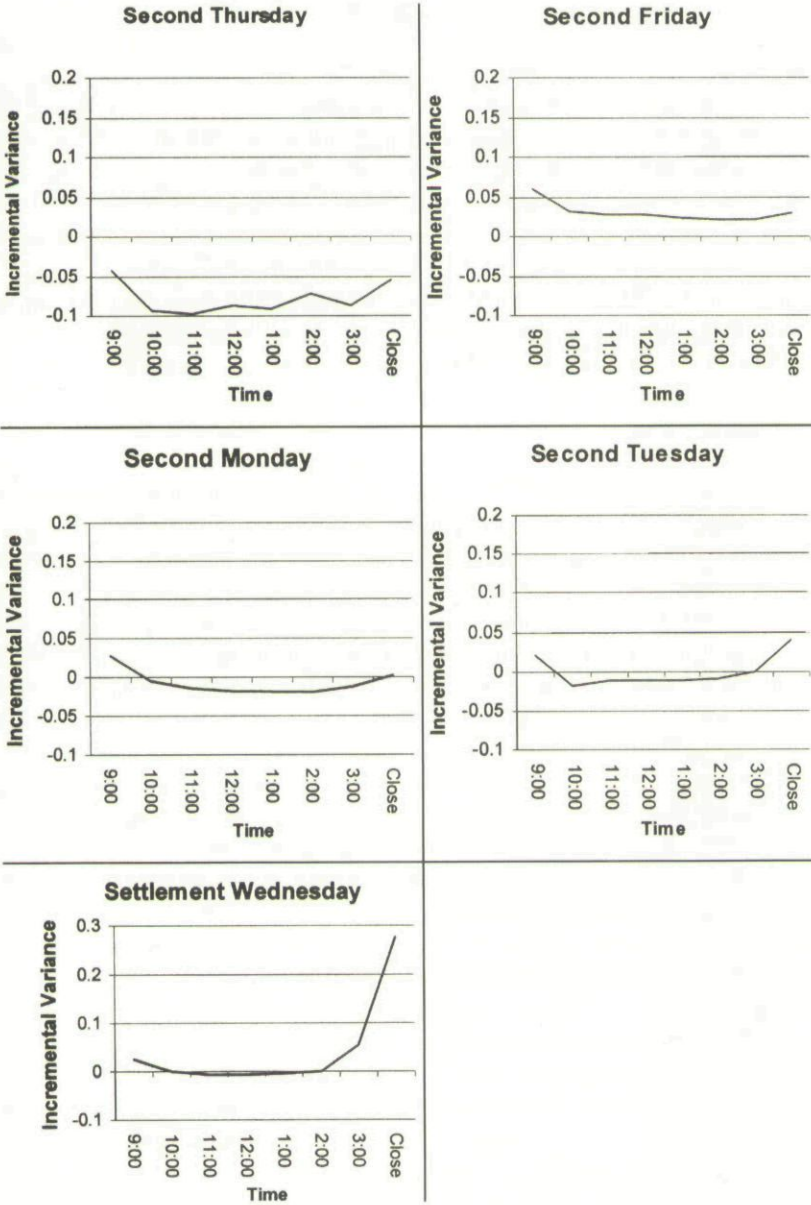


FIG. 1 (Continued)

desk is able to disguise its trading motives when it trades on private information.¹⁹

V. Discussion of Results and Implications

The goal of this article is to test whether the reverse-J pattern for volatility can exist in the absence of private information. To avoid the difficulty of identifying different trader types in equity markets, we examine intraday patterns in the broker market for overnight Fed funds. The unique rules and limited market entry provide a tightly defined experimental setting in terms of the theoretical issues related to the reverse-J pattern. The unique rules and limited market entry create a persistent pattern in rate changes over the 2-week reserve maintenance period, which means that if any private information about future returns (or interest rate changes in this market) exists, it is exceedingly difficult to exploit. Thus, private information is not a pricing factor in the Fed funds market. Accordingly, in this market, all the traders are discretionary liquidity traders, and the primary objective in trading is successful settlement with the Federal Reserve.

We use a Glosten et al. (1993) GARCH model that models asymmetry in the variance term. This model is chosen because of its simplicity and ability to account for ARCH and GARCH effects, which are shown to be important in Fed funds by Hamilton (1996) in daily average rates and by Cyree and Winters (2001) in hourly rates. Our results provide convincing evidence that the intraday pattern in Fed funds variances is consistent with the previously identified pattern in the microstructure literature, which is that the largest intraday variances occur at the open and the close of trading. We also provide evidence that the pattern is not because of GARCH effects. The focus of most of the theories that have developed to explain this intraday pattern is private information about future security returns. However, private information about future returns does not play a role in Fed funds rate changes.

Our results suggest that private information is not a necessary condition for the reverse-J pattern. Instead, our results support the model by Brock and Kleidon (1992), who suggest that information arrives during the overnight nontrading period that causes the end-of-the-day position to deviate from the optimal position, necessitating trading at the open. Brock and Kleidon (1992) also indicate that the optimal position at the close is different from the optimal position during trading hours, which necessitates trading at the close in preparation for the overnight nontrading period. The institutional features of the Fed funds market clearly fit the trading behavior described in the Brock and Kleidon (1992) model.

Our results do not state that private information does not play a role in

19. See Singh and Zak (1992) for a discussion of the need of the open market desk to disguise its open market interventions to protect its private information, and of how the desk can disguise its trading on private information.

intraday patterns in other securities markets but, rather, that private information is not a necessary condition for the observed intraday pattern. Admati and Pfleiderer (1988) suggest that private information creates trading clusters, and Hong and Wang (2000) suggest that trading will cluster at the open and close in markets with private information and overnight trading stops. Thus, private information may have a role in the size and shape of the observed reverse-J patterns. However, our findings suggest that periodic closures can cause the empirically verified reverse-J intraday pattern in the absence of exploitable private information. One implication of our findings is that the increased volatility resulting from periodic market closures could be mitigated by avoiding market closure and, instead, by having 24-hour trading.

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