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George J. Jiang,[1] Ingrid Lo,[2] and Adrien Verdelhan[3]

[1]Department of Finance
Eller College of Management
University of Arizona
Tucson, AZ 85721-0108
gjiang@email.arizona.edu

[2]Financial Markets Department
Bank of Canada
Ottawa, Ontario, Canada K1A 0G9
ingridlo@bankofcanada.ca

[3]Department of Economics
Boston University
Boston, MA 02215
av@bu.edu

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Abstract

We examine large price changes, known as *jumps*, in the U.S. Treasury market. Using recently developed statistical tools, we identify price jumps in the 2-, 3-, 5-, 10-year notes and 30-year bond during the period of 2005-2006. Our results show that jumps mostly occur during pre-scheduled macroeconomic announcements or events. Nevertheless, market surprise based on pre-announcement surveys is an imperfect predictor of bond price jumps. We find that a macroeconomic news announcement is often preceeded by an increase in market volatility and a withdrawal of liquidity, and that liquidity shocks play an important role for price jumps in U.S. Treasury market. More importantly, we present evidence that jumps serve as a dramatic form of price discovery in the sense that they help to quickly incorporate market information into bond prices.

JEL classification: G12, G14
Bank classification: Financial markets

Résumé

Les auteurs s'intéressent aux fortes variations de prix, ou « sauts », qui surviennent sur le marché des obligations du Trésor américain. Au moyen d'outils statistiques récents, ils identifient les sauts enregistrés par les prix des obligations à 2, 3, 5, 10 et 30 ans au cours des années 2005 et 2006. Leurs résultats montrent que la plupart des sauts se produisent les jours où des données macroéconomiques doivent être annoncées. Cependant, les variations inattendues, déterminées à partir d'enquêtes menées dans les jours antérieurs à une annonce, constituent un indicateur imparfait des sauts à venir sur le marché des obligations du Trésor américain. Les auteurs constatent plutôt que les annonces macroéconomiques sont souvent précédées d'une accentuation de la volatilité du marché et d'un recul de la liquidité, et que les chocs de liquidité permettent d'expliquer une bonne part des sauts observés sur le marché. Fait encore plus important, ils notent que les sauts jouent un rôle crucial dans le processus de découverte des prix, puisqu'ils contribuent à intégrer rapidement aux prix des obligations l'information disponible sur le marché.

Classification JEL : G12, G14
Classification de la Banque : Marchés financiers

I. Introduction

Recent studies provide strong empirical evidence that interest rates contain "surprise elements" or jumps.[1] It is well-known that compared to continuous price changes, jumps have distinctly different implications for the valuation of derivative securities, risk management, as well as portfolio allocation. Thus, it is important to understand what drives jumps in bond prices, and how the market behaves prior to and post significant price changes. In this paper, we identify jumps in the U.S. Treasury bond prices using recently developed statistical tools. The data used in our study is obtained from the BrokerTec electronic trading platform and contains around-the-clock trades and quotes for the on-the-run 2-year, 3-year, 5-year, and 10-year notes and 30-year bond.[2] Based on 5-minute data over the period of 2005-2006, we identify 60 out of 477 trading days where the 2-year note experiences jumps in prices. On 8 of these 60 days, the 2-year note has multiple jumps in prices. The largest jumps in price are, respectively, 0.24% on the upside and -0.17% the downside (compared to an average 5-minute return standard deviation of 0.006%). Price jumps on longer maturity bonds are of larger magnitude. For example, the largest positive jump and negative jump in price are, respectively, 0.70% and -0.64% for the 10-year note, while those for the 30-year bond are 2.13 % and -3.55% respectively.

A natural question then is what causes these large jumps in bond prices? We identify the intra-day jumps of US treasury securities and then examine to what extent jumps can be attributed to macroeconomic news announcements. In this aspect, our approach is similar to that of Fleming and Remolona (1997) with a focus on large changes in bond prices.[3] Consistent with existing studies, we find that a large number of jumps occurs during pre-scheduled macroeconomic news announcements. An additional advantage of our study is that, by identifying jumps first we can then search for potentially

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[1] There is now a growing body of literature that explicitly incorporates jumps in modeling the term structure dynamics of interest rate. For example, Das (2002) extends the Vasicek (1977) model to a jump-diffusion model and shows that incorporating jumps captures many empirical features of the Fed Funds rate that can not be explained by the continuous diffusion models. Johannes (2004) finds significant evidence for the presence of jumps in the 3-month Treasury bill rate. Piazzesi (2001, 2005) models the Fed's target rate as a jump process.

[2] During our sample period, the BrokerTec electronic trading platform accounts for about 60% of trading activity for these securities.

[3] Fleming and Remolona (1997) examine the twenty-five largest price changes in the on-the-run 5-year U.S. Treasury note from August 1993 to August 1994 and find that they are all associated with news announcements.

related news/events. Indeed, compared to existing literature, we document a more extensive list of pre-scheduled macroeconomic news/events that are potentially responsible for bond price jumps.[4]

Most importantly, our methodology allows us to directly examine the relation between jumps and announcement surprises.[5] Existing studies document that surprises in news announcements or unexpected macroeconomic shocks often result in large changes of bond prices. For instance, Andersen, Bollerslev, Diebold and Vega (2003), Balduzzi, Elton and Green (2001), Green (2004), Menkveld, Sarkar and van der Wel (2006) and Pasquariello and Vega (2006) find that announcement surprises have a strong impact on bond prices. Sorting jumps into 5 groups according to absolute returns, we find that absolute jump return is not a simple monotonic function of announcement surprises. That is, announcement surprise is not directly indicative of jumps. For example, for the 5-year note the group with the largest jump size has the lowest announcement surprise. Rather intriguingly, we find that the number of jumps and jump size are positively related to the extent of liquidity withdrawal or liquidity shocks prior to the news announcement. We measure liquidity withdrawal by the widening of bid-ask spread and the withdrawal of depth from the order book prior to macroeconomic news announcements. Holding announcement surprise constant, our results suggest that a higher liquidity shock is in general associated with more jumps and larger absolute return for all maturities.

To further examine whether liquidity shocks have predictive power for jump frequency, we specify and estimate a Probit model. The estimation results show that liquidity shocks have significant predictive power for jump frequency. Interestingly, even after explicitly controlling for the effect of announcement surprises, liquidity shocks remain significant in explaining jumps. Thus, our results show that beyond announcement surprises, liquidity shocks prior to news announcements play an important role for jumps in the US treasury market.

Finally, we examine the post-jump price discovery process in the bond market. Our work is closely related to recent studies that examine the information content of order flow around announcements on

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[4] For example, we document that jumps are potentially associated with the announcement of NY Empire State Index which, to our knowledge, has not been included in any existing studies.

[5] Surprises in news announcements are often measured by the difference between the one-week ahead survey and the actual announcement. The survey data offers a measure of market expectations for certain macroeconomic news, and thus measures of both expected and unexpected components in the announcement.

the treasury bond market. Green (2004) finds that order flow has a higher information content on announcement days in the 5-year Treasury note relative to non-announcement days. Menveld, Sarkar and van der Wel (2006) provide similar findings for 30-year Treasury bond futures. These studies focus on comparing the informational role of order flow on announcement versus non-announcement days. We extend these studies by examining the effect of jumps on the price discovery process. Our results show that for the most actively traded 2-, 5- and 10-year notes, order flows have significantly less price information after jumps during announcement days compared to the case where there is no jump at the announcements. In particular, order flow contains less information during the 15-minute interval immediately after jumps than during the 60-minute interval after jumps. Moreover, this lessened informational role for order flow during the 15 min interval after a jump is accompanied by a surge of trade volume. Therefore, the smaller informational role of order flow should not be due to lack to trading and stagnant price discovery. Taken together, the results suggest that jumps help to quickly incorporate information into bond prices.

The rest of the paper proceeds as follows. Section II describes the data and jump test. Section III presents empirical results of identified price jumps in the U.S. Treasury market, and market activities around jumps. Section IV examines the role of liquidity shocks in bond prices jumps as well as post-jump price discovery process. Section V concludes.

II. Data and Methodology

A. Data

The US Treasury securities data are obtained from BrokerTec, an interdealer electronic trading platform in the secondary wholesale US Treasury securities market. Since 2003, the majority of secondary trading has gone through electronic platforms with over 95 % of active issue treasuries occurs on electronic platform.[6] Two platforms dominate the US treasuries market: BrokerTec and E-speed. BrokerTec has a market share of 60-65% on the active issues and is more active in the trading of 2 years, 3 years,

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[6] See “Speech to the Bond Market Association”, December 8, 2004 by Michael Spencer, founder and chief executive of ICAP.

5 years and 10 years treasury notes. The data also include the 30-year bond, although E-speed has a larger market share for this maturity. There was strong growth in trading volume on the BrokerTec platform in the past years. The average daily trading volume of all the maturities goes up from $30.9 billion in 2003, $53.0 billion in 2004, $80.2 billion in 2005, to $103.4 billion in 2006. The BrokerTec platform functions as a limit order book. Traders can submit limit orders, i.e., orders that specify both price and quantity posted on the book, or they can submit marketable limit orders, i.e., orders with a better price than or equal to the best price on the opposite side of the market, to ensure immediate execution. The orders remain in the market until matched, deleted, inactivated, loss of connectivity, or market close. The market operates more than 22 hours a day from Monday to Friday. After the market closes at 5:30 p.m. (EST), it opens again at 7:00 p.m. (EST). Limit order submitters can post "iceburg" orders, in which only part of their order are visible to the market and the remaining part is hidden. All orders on the book except the hidden part of the orders are observable to market participants. The data set contains the tick-by-tick observations of transactions, order submissions and order cancellations. It includes the time stamp of the observations, the quote, the quantity entered and deleted, the side of the market and the aggressor indicator in case of a transaction.

We use data from 7:30 a.m. EST to 5:00 p.m. EST since trading is more active during this time interval. This interval also contains all pre-scheduled U.S. news announcements, and it provides us with 9.5 hours of trading and 114 five-minute return observations each day. Since liquidity has changed drastically over time, we restrict our analysis to the most recent period of our sample, i.e., from January 2, 2005 to December 29, 2006. Days with early closing before public holidays are also excluded as liquidity is typically low for these days. The dataset consists of over 465.5 million observations and 10.9 million transactions.

Table I provides descriptive statistics of the data. Since the order book contains the price schedule on both sides of the market, there are multiple ways to measure liquidity supply. We compute and report spread, daily trading volume (in $billions), trading duration (in seconds), daily return volatility, depth at the best quote, depth of the entire book, and hidden depth. Spread is defined both in relative term and in ticks. Relative spread is defined as

$$\text{relative spread} = (\textit{best bid price} - \textit{best ask price})/\textit{mid-quote} \tag{1}$$

and measured at the end of each 5-minute interval and averaged over the trading day. Spread in ticks is also measured at the end of each 5-minute interval and averaged over the trading day. As mentioned in Fleming and Mizrach (2007), the tick size of different maturities differs. The tick size of the 2-year, 3-year and 5-year note is 1/128 whereas that of the 10-year note and 30-year bond is 1/64. Daily return volatility is calculated as the square-root of the sum of squared log mid-quote difference sampled at 5-minute intervals

$$\text{return volatiilty} = (\sum_{i=1}^{114} (\ln p_i - \ln p_{i-1})^2)^{1/2} \tag{2}$$

where the mid-quote, p_i, is defined as mid-quote $= (\textit{best bid price} + \textit{best ask price})/2$. The average (hidden) depth (in millions) at the best bid/ask is the total (hidden) observable depth at the best price on both the bid and ask side of the market measured at the end of each 5-minute interval and averaged over the trading day. The average depth and average hidden depth in the entire order book are defined similarly.

BrokerTec is a highly liquid platform over our sample period from 2005-2006. As shown in Table I, relative spread is smallest for the 2-year note with a sample mean of less than 0.0083% among the actively traded securities, followed by the 5-year note (0.0119%) and 10-year note (0.0179%). The spread in ticks is consistent with the relative spread. Trading volume is heaviest for the 2-year note ($27.45 billion per day), followed by the 5-year note ($24.69 billion per day), and 10-year note ($22.76 billion per day). In terms of trading duration, the 10-year note is most frequently traded, with an average duration of 6.59 seconds. This is closely followed by the 5-year note at 6.74 seconds. The trading duration of the most heavily traded 2-year note is on average 15.99 seconds. The result suggests that the average trade size is larger for the 2-year note than the 5-year and the 10-year note.

Return volatility is generally increasing with maturity. The trend seems related to where the depth accumulates on the order book. The mode of depth for the 2-year note locates closest to the best price, on average around 1.18 tick away from the best price on both sides of the market. As maturity increases, depth mode locates further away from the best price: 1.25 tick for the 3-year note, 1.67 tick for the 5-year note, 1.53 tick for the 10-year note, and 2.68 tick for the 30-year bond. Thus normal price movements are more likely to be restricted by depth aggregated at the mode. The finding is consistent with Kavacjecz and Odders-Whilte (2004) in the equity market where accumulation of depth at a price level restricts the range of normal price changes.

The 2-year note has the deepest book both at the best price ($637.72 million) and total depth ($5122 million). Hidden depth is low in general: hidden orders at the best price consist of less than 5% of the observable depth at the best price for the 2-year, 5-year, and 10-year notes.

Figure 1 presents the intra-day activities in the 2-year note. The intra-day patterns for the other bonds are similar and thus not reported for brevity. Consistent with the findings in Fleming (1997), trading volume peaks first in the 8:30 to 10:00 EST interval and goes up again from 13:00 to 14:00 EST. These two intervals overlaps with major macroeconomic announcements. Trading duration shows the reverse pattern of trading volume. The arrival of a trade takes longer at the end of the day, averaging over 40 seconds. At the most hectic interval from 8:30 to 9:00 EST, it takes on average less than 5 seconds for a trade to arrive. Relative spread is higher at the beginning (before 8:30 EST)) and end of the trading day (after 16:00 EST). The depth at the best price is thinner before 8:30 EST and after 15:00 EST. For the rest of the day, the book is on average over 600 millions. The level of hidden depth is higher at noon and it goes up again after 15:00 EST. This finding suggests that market participants hide more of their orders when there is less depth in the market.

Data on macroeconomic news announcements and the survey of market participants comes from Bloomberg and Briefing.com economic calendar. We cover an extended list of announcements and include both announcements used in previous literature and announcements where jumps are detected. To ensure the list of announcements is comprehensive, we start with the 25 announcements from Pasquariello and Vega (2006). We then check whether the timing of each jump coincides with any other announcements using information from the Briefing.com economic calendar, which features a comprehensive list of pre-scheduled announcements. This way, we include additional 7 economic announcements: FOMC minutes, ISM service, NY Empire State Index, Chicago PMI, Existing Home Sales, Philadelphia Fed Index, and ADP National Employment report. In addition to pre-scheduled news announcement, we also collect the auction times of 2-year, 3-year, 5-year and 10-year notes. Lastly, we collect the release of the testimony of Semiannual Monetary Policy Report and Economic Outlook. Following Balduzzi, Elton and Green (2001) and Andersen Bollerslev, Diebold and Vega (2003), the standardized news surprise is defined as

$$S_{kt} = \frac{A_{kt} - E_{kt}}{\hat{\sigma_k}} \tag{3}$$

where A_{kt} is the actual announcement, E_{kt} is the median forecast for news k on day t and $\hat{\sigma_k}$ is the standard deviation of $A_{kt} - E_{kt}$.

B. Statistical Tests of Jumps

A number of statistical tests have been proposed in the literature to detect whether there are jumps in asset prices. For instance, Aït-Sahalia (2002) exploits the restrictions on the transition density of diffusion processes to assess the likelihood of jumps. Carr and Wu (2003) make use of the decay of the time value of option with respect to option maturity. More recently, Barndorff-Nielsen and Shephard (2004, 2006) propose a bi-power variation (BPV) measure to separate the jump variance and diffusive variance. Lee and Mykland (2007) exploit the properties of BPV and develop a rolling-based nonparametric test of jumps. Jiang and Oomen (2007) propose a jump test based on the idea of "variance swap" and explicitly take into account of market microstructure noise. Aït-Sahalia and Jacod (2007) propose a family of statistical tests of jumps using power variations of returns.

In this study, we employ two jump tests developed in recent literature, namely, the "bi-power variation" (hereafter BPV) approach by Barndorff-Nielsen, and Shephard (2004, 2006), and the "variance swap" (hereafter SWV) approach by Jiang and Oomen (2007). Both tests are developed using high frequency data to test for the presence of jumps during a particular time period, e.g., a day. In addition, both BPV and SWV jump tests are developed in a "model-free" framework in the sense that it applies to a very general asset price process as specified in (13) in the appendix. Note that for the process specified in (13), there are no particular structures imposed on the drift term, the diffusive volatility component, or jump component. Simulations performed in Jiang and Oomen (2007) show the "bi-power variation" and "variance swap" tests have similar finite sample properties in size but different finite sample properties in power. Both tests tend to over-reject the null hypothesis of no jumps. In general, the SWP test has more power in detecting infrequent jumps with large size during a day while the BPV test can pick up frequent jumps with small sizes during a day. Thus, we combine both tests in our empirical analysis for more desirable finite sample properties.

Throughout the paper, we assume that bond prices are observed at regular time intervals $\delta = 1/N$ over the period $[0, 1]$. The conventional realized variance (RV) is defined as:

$$RV_N = \sum_{i=1}^{N} r_{\delta,i}^2,$$

where $r_{\delta,j} = \ln(S_{j\delta}/S_{(j-1)\delta})$, see Andersen, Bollerslev, Diebold, and Labys (2003), and Barndorff-Nielsen and Shephard (2004). It is well known that $\operatorname*{plim}_{N\to\infty} RV_N = V_{(0,1)} + \int_0^1 J_u^2 dq_u$, where $V_{(0,t)} \equiv \int_0^t V_u du$. In words, RV is a consistent estimator of the total variance including both the continuous diffusive component and the discontinuous jump component.

The bi-power variation (BPV) measure defined in normalized form is given by:

$$BPV_N = \frac{1}{\mu_1^2} \sum_{i=1}^{N-1} |r_{\delta,i+1}| \, |r_{\delta,i}| \, ,$$

where $\mu_p = 2^{p/2}\Gamma\left((p+1)/2\right)/\sqrt{\pi}$ for $p > 0$. Barndorff-Nielsen and Shephard (2004) show that $\operatorname*{plim}_{N\to\infty} BPV_N = V_{(0,1)}$. That is, the BPV only captures the diffusive variance component. Based on this, the following jump test is proposed in Barndorff-Nielsen, and Shephard (2006):[7]

$$\frac{V_{(0,1)}\sqrt{N}}{\sqrt{\Omega_{BPV}}} \left(1 - \frac{BPV_N}{RV_N}\right) \xrightarrow{d} \mathcal{N}(0,1). \tag{4}$$

As detailed in the appendix, feasible versions of the above tests can be obtained by replacing Ω_{BPV} and $V_{(0,1)}$ with robust and consistent estimates, for instance, $\widehat{\Omega}_{BPV}^{(4)}$ and BPV_N respectively.

The "variance swap" jump test developed in Jiang and Oomen (2007) is based on an intuition long established in the finance literature: in the continuous-time limit, the difference between simple return and log return equals one half of the instantaneous variance. This basic idea has been explored in the "variance swap" literature. Specifically, Neuberger (1994) proposes a strategy to perfectly replicate

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[7] Simulations in Huang and Thauchen (2006) for the BPV test and Jiang and Oomen (2007) for the SWV test show that among various test statistics, the ratio tests of both approaches have the best finite sample performance. As a result, our empirical analysis is based on the ratio tests.

"variance swap" by dynamically trading on "log-price" contracts. However, when there are jumps in the price process, this replication strategy fails, and the gain/loss of the replication strategy is a function of jumps. Using discretely observed asset prices, the following "variance swap" (SwV) measure can be constructed:

$$SwV_N = 2\sum_{j=1}^{N}\left(R_{\delta,j} - r_{\delta,j}\right) = 2\sum_{j=1}^{N} R_{\delta,j} - 2\ln\left(S_1/S_0\right), \tag{5}$$

where $R_{\delta,j} = (S_{j\delta} - S_{(j-1)\delta})/S_{(j-1)\delta}$. As detailed in the appendix, the difference between the variance swap measure (SwV_N) and the realized variance measure (RV_N) captures the presence of jumps and forms the basis of "variance swap" jump test. The SWV approach is based on:[8]

$$\frac{V_{(0,1)}N}{\sqrt{\Omega_{SwV}}}\left(1 - \frac{RV_N}{SwV_N}\right) \xrightarrow{d} \mathcal{N}(0,1) \tag{6}$$

where $\Omega_{SwV} = \frac{1}{9}\mu_6 X_{(0,1)}$ and $X_{(0,T)} = \int_0^1 V_u^3 du$. Consistent and robust estimators of the asymptotic variance is given in the appendix. When the test statistics of both approaches are significant (at 1% critical level), we reject the null hypothesis of no jumps.

Once the jump tests reject the null hypothesis of no jumps in a day, we follow a sequential approach to identify jump returns. As acknowledged in the literature, pinpointing exactly which returns are singled out as jumps is a difficult task. Since volatility is time-varying and clustering, returns of the largest magnitude are not necessary jumps. In this paper, we propose a sequential approach to identify jump returns during a day. Details of the procedure is given in Appendix A. As noted earlier, since our tests are performed on high frequency intraday returns, the data is likely subject to significant market microstructure effect. In both jump testing and jump identification, we take into account of potential market microstructure noises when implementing the tests. In particular, in the first step we allow for measurement error (i.e. asset price is observed with noise) in the SWV test, whereas in the second step we take into account discrete price changes due to tick-size and bid-ask spread. Details can be found in Appendix A.

We evaluate the performance of jump tests using simulations. Each "day" we simulate a jump-diffusion process with stochastic volatility, and then implement the jump tests. We examine the size

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[8] Simulations in Lee and Mykland (2007) show that the SWV test and their proposed approach share similar powers of identifying jumps in most common settings.

and power of the BVP test, SwV test and joint-test approach under different jump sizes and seven specifications with different parameter values for the mean reversion of volatility, volatility-of-volatility and "leverage effect". The design of the simulation is described in detail in Appendix B. The simulation results are based on 10,000 replications. The results in Table A shows that at 1% critical level, both the BPV and SWV tests tend to over reject the null hypothesis of no jumps with the size clearly above 1%. However, the size of the joint BPV and SWV tests is much improved, generally below but closer to 1%. Thus, the joint approach substantially mitigates the size problem. As expected, the combined test has lower power. However, the power of the joint test approach is similar to the other two test when the jump size is large (about 5 times of return standard deviation). In this case, the joint test procedure does not sacrifice much of the power and works well in picking up large jumps. The conservativeness of the joint test approach suits our purpose as we are interested in large price changes in the U.S. treasury security market.

III. Empirical Results

In this section, we first present the characteristics of all jumps. Then we identify how jumps are associated with a pre-scheduled news announcement/events.

A. Jumps in Bond Prices

Table III reports the jump frequency, the statistics of jump size of bond prices for different maturity and the number of concurrent jumps across maturities. Among the three most liquid securities, the 5-year note has the highest jump frequency with 72 jumps, followed by the 2-year note with 69 jumps, and the 10-year note with 63 jumps. The jump size generally increases with maturity with the mean absolute jump size going up from 0.08% for the 2-year note, 0.16% for the 5-year note, to 0.28% for the 10-year note. This pattern is consistent with Balduzzi, Elton and Green (2001) who find that the size of price change as a result of announcement surprise is increasing with maturity. Relative to daily return volatility reported in Table I, the jumps represent dramatic price changes. Separating positive jumps from negative ones, there is no clear difference in terms of frequency and jump size.

How often do jumps occur the same time across maturities? The last panel of Table III shows the concurrent jumps across maturities. Jumps across two different maturities are defined as concurrent if they are less than 5-minute apart from each other. Across maturities, there is a strong concurrence of jumps in bond prices. For example, out of the 69 jumps at the 2-year note prices, 70% of them have concurring jumps at the 3-year maturity. Extending the window of defining concurrent jumps would further increase the number of concurring jumps across maturities. We note that here we simply documents whether jumps identified on different maturities overlap with each other in time. The issue of co-jumps across maturities is formally examined in Dungey, MacKenzie and Smith (2007) and Lahaye, Laurent and Neely (2007). Dungey, MacKenzie and Smith (2007) examine co-jumps across maturities using the E-speed data. Lahaye, Laurent and Neely (2007) examine co-jumps across asset markets.

B. Jumps and Macroeconomic News Announcements

We further examine how often jumps occur at pre-scheduled news announcement times. A jump is identified as occurring at an announcement time if the 10-minute window centered around the announcement time overlaps with the 5-minute jump return interval. With a 10-minute window, we allow for potential variations (such as recording errors) in announcement time.

Table IV shows that a large majority of jumps occur during announcement time. For example, more than 90% of jumps of the 2-year note occur during pre-scheduled announcement time. Although the number of jumps outside of announcement time is small, the median jump sizes are overall comparable to those at a pre-scheduled announcement time. We examine in more detail later in the section the possible causes of such jumps outside announcements.

Panels C and D of Table IV report the number of concurrent jumps across maturities according to whether the jumps occur at announcement times or not. The frequency of concurrent jumps is higher for jumps occurring at announcement time. The findings suggest that macroeconomic news is the driving factor of common jumps across maturities.

The left column of Figure 2 shows the distribution of jumps through the trading day for the 2-year and 5-year notes. The spikes appear at 8:30, 10:00 and less distinctively around 14:00, corresponding to the standard pre-scheduled announcement times. The right column of the figure shows the distribution of jumps not occurring at announcement times. The distribution is, in general, flat over the day. This conforms to the intuition that jumps not occurring at announcement times are unexpected – they could be related to sudden arrival of information or changes in liquidity conditions in the market. The plots for other maturities showed essentially the same patterns.

To pinpoint exactly what drives jumps in bond prices, we first focus on jumps occurring at an announcement time. Panel A of Table V reports the top 15 announcements with the most simultaneous jumps. Bond price jumps in response to important announcements such as Change in Non-farm Payroll, Consumer Price Index, Producer Price Index, Consumer Confidence, and ISM index. These announcements are generally consistent with those identified as having significant impact on bond price changes in the existing literature, such as Balduzzi et. al. (2001), Green (2004), Pasquariello and Vega (2006) and Menkveld et al.(2006). More importantly, our methodology does not need to predetermine the list of announcements deemed important as in the previous literature and we uncover news announcements associated with jumps that have not been examined in the previous literature. For example, the announcement of NY Empire State Index and FOMC minutes, to our knowledge, has not been included in any existing studies. We also uncover other announcements associated with jumps (not listed on Table 5), which have not been documented in the literature before: ISM service, Chicago PMI, Existing Home Sales, Philadelphia Fed Index, ADP National Employment report, the release of the testimony of Semiannual Monetary Policy Report and Economic Outlook. The mean jump size of most of these announcements are comparable to the median announcement jump size.

Is announcement surprise indicative of jumps? Existing literature documents empirical evidence that a larger surprise tends to have a bigger impact on bond prices. Green (2004) groups cumulative transaction returns based on announcement surprise and shows that a larger surprise is associated with a bigger change in return in purchase transactions. We go one step further to examine how jumps are associated with announcement surprise. For each maturity, we sort jumps on announcement days into 5 groups according to the absolute jump return, and report the mean absolute jump return, mean absolute announcement surprise as defined in (3), and number of significant surprises (i.e., survey error larger than 1 standard deviation) for each group in Panel B of Table V. For the cases in which jumps are associated with multiple announcements at the same time, we pick the announcement with the highest absolute surprise. Except for the 30-year bond, a higher announcement surprise is not indicative of jumps. The absolute mean surprise in general does not increase monotonically with the mean absolute jump return. In fact, the lowest mean absolute surprise occurs in the highest absolute mean jump return group for the 5-year note.

While jumps outside announcement times could be attributed to unexpected information / news arrival or liquidity shocks in general, it turns out not always so easy to pinpoint the exact cause of jumps even as an ex post check. Nevertheless, as a further attempt to understand jumps outside pre-scheduled news announcements, we search the news archive FACTIVA for potentially related news/events. FACTIVA offers a comprehensive news collection from the Wall Street Journal, the Financial Times, Dow Jones, Reuters newswires and the Associated Press. The following representative headlines illustrate a variety of unanticipated news/events that can potentially trigger jumps in the 10-year note.

- 02/28/2005: '10-year note slid 22/32 in price, driving yields up to 4.36 percent from 4.27 percent. No specific news found.'
- 05/04/2005: 'Longer-dated Treasury debt plummeted after the government startled investors by saying it was considering resuming issuance of 30-year bonds.'
- 03/28/2006: 'U.S. Treasury bond investors digest a Federal Reserve policy statement, crafted with new Fed Chairman Ben Bernanke at the central bank's helm, suggesting more interest rate hikes..'
- 09/19/2006: 'Bond investors bet heavily on a Federal Reserve Interest rate cut soon.'

Figure 3 shows the market characteristics around the above jumps. The jump on March 28, 2006, which occurs 15 minutes after the FOMC decision, represents a reversal of the initial drop in bond price. For most of the jumps, we observe the following patterns: (i) post-jump returns fluctuate around zero. That is, there is no immediate correction to these large price changes. (ii) trading volume increases in general around the jump interval. We will next examine in more detail market activities around jumps and the differences between jumps occurring at pre-scheduled news announcement time and those outside pre-scheduled news announcements.

C. Market Activities Around Jumps

Figure 4 depicts the market activities around jumps in the 2-year note. The plots for other maturities have similar patterns. The left column focus on announcement days, contrasting days with jumps versus those without. For clean comparison, our analysis excludes days with multiple jumps. The right column plots market activities around jumps occurring outside pre-scheduled announcement times. The following summarizes the findings in Figure 4.

- *The Announcement Effect*: Consistent with Balduzzi, Elton and Green (2001), Fleming and Remolona (1999) and Green (2004), trading volume is low during the pre-announcement period and more than doubles right after the announcement. Also consistent with the findings in Balduzzi, Elton and Green (1999) and Green (2004), return volatility, defined as the average of absolute change in logarithmic price, starts to rise in the 5-minute interval before an announcement and then peaks at the announcement time. Spread peaks in the 5-minute interval before the announcement.

  Both the depth at the best price and overall depth withdraws from the market before an announcement. They drop to the lowest level in the 5-minute interval before announcements and come back to the normal level after the announcement. Similar to the observable depth, hidden depth at the best price withdraws from the market before announcement. That is, market participants withdraw orders to protect themselves against upcoming uncertainty.

- *The Jump Effect*: When a jump occurs at an announcement time, the increase in trading volume is even more dramatic. Trading volume at the announcement with a jump nearly doubles that without jumps at the jump-interval and immediately after the jump. Similarly, the pre-announcement increase in volatility is higher when jump occurs at an announcement time than when no jump occurs. The widening of spread more than doubles before an announcement with jumps compared to those without jumps. This suggests that before jumps occur, market participants place their best orders further out and a large price change occurs either when (i) a market order hits the existing limit orders following the announcement or (ii) new limit orders come in and set a new price moving the existing mid-quote up /down. This mechanism depends on how far the market participants withdraw from their existing best price, which in turn depends on the expectation of market participants regarding the upcoming announcement. This mechanism could be at play with or without significant announcement surprises. Thus the finding provides a potential explanation for imperfect relation between news surprise and price jumps.

Both depth at the best prices and overall depth are slightly lower before jumps occurring at announcement time than when no jumps occur. This withdrawal of depth at the best quote before an announcement could contribute to large price changes when market orders erode the thin depth once the announcement is realized. Hidden depth is larger before an announcement with a jump especially at the best quote. This suggests that market participants place more hidden depth at the best price when facing more uncertainty.

- *Jumps outside of an Announcement Time*: Similar to jumps at an announcement time, trading volume increases at jumps outside of an announcement time. However, in contrast to the case of jumps at an announcement we do not observe any volatility increase before these other jumps. It peaks suddenly at the jump interval and quickly goes back to normal level after jump. This may suggest that non-announcement jump are triggered by unanticipated information or events or simply liquidity shocks. Also, in contrast to jumps occurring at announcement time, spread fluctuates around a stable level before and after non-announcement jumps. This is further evidence that market participants in general do not anticipate these jumps.

  Unlike in the case of jumps at announcements where both depth at the best quote and the overall depth increase after jumps, they actually drop to lower levels in the 5-minute interval after jumps occurring outside of an announcement time. It seems to suggest that after the jumps, market participants either withdraw depth from the market or do not replenish the depth in the midst of uncertainty of the nature of jump. Interestingly, the depth of hidden orders at the best bid and ask quotes are virtually zero around non-announcement jumps. After the jump, hidden depth at the best quotes does not come back to the market immediately. It is likely that the nature of these jumps is not immediately revealed to the market, thus market participants refrain from submitting best hidden depth after jumps to protect their positions.

IV. Further Analysis

A. Information Shocks vs. Liquidity Shocks

In this section, we assess the role of information shocks and liquidity shocks in price jumps. Information shocks, measured by news surprises, and liquidity shocks can both contribute to jumps in bond prices. Liquidity shocks here carry a broader meaning than in the conventional sense. They could arise due to pure trading imbalance or order withdrawal as a result of information uncertainty. An obvious example of the later case is the decrease in market depth before an announcement. To examine the interaction between information shocks and liquidity shocks, we focus on announcement days. We first sort and divide the announcements into 3 equal groups according to the pre-announcement liquidity shocks defined below. Then within each group, we further sort and divide the announcements into 3 equal subgroups according to the absolute announcement surprise. Motivated by findings for spread and depth before jumps, we define two variables to capture the liquidity shocks:

- Standardized shock to spread, $sprdshk_{t-1}$, is defined as the difference between spread in period $t-1$ and the mean of spread from $t-6$ to $t-2$, scaled by the standard deviation of the difference.

  $$sprdshk_{t-1} = \frac{spread_{t-1} - \frac{1}{5}\sum_{j=2}^{6} spread_{t-j}}{\sigma_{spread}}, \tag{7}$$

  where $spread_{t-j}$ is the spread at the end of interval $t-j$ and σ_{spread} is the standard deviation of $spread_{t-1} - \frac{1}{5}\sum_{j=2}^{6} spread_{t-j}$. This measure captures the withdrawal of best quotes before a jump.

- Standardized shock to overall depth, $dpthshk^{overall}_{t-1}$, is defined similarly as

$$dpthshk^{overall}_{t-1} = \frac{depth^{overall}_{t-1} - \frac{1}{5}\sum_{j=2}^{6} depth^{overall}_{t-j}}{\sigma_{depth}}, \tag{8}$$

  where $depth^{overall}_{t-j}$ is the overall observable depth measured at the end of $t-j$. This measure captures the withdrawal of overall observable depth.

Panel A of Table VI shows the results associated with the depth shock and Panel B shows the results associated with the spread shock. The results of the two panels are qualitatively similar so we focus our discussion on the depth shock. There are several interesting findings. First, both absolute returns and the number of jumps increase with liquidity shocks. Furthermore, with large pre-announcement liquidity shocks, jumps are more likely regardless of the level of surprise. This is especially true for the most liquid 2-, 5- and 10-year notes when we compare the highest liquidity shock group with the lowest liquidity shock group. The mean absolute announcement surprises across the highest liquidity group and the lowest liquidity group are of similar magnitude. Yet the number of jumps in the highest liquidity shock group are almost always larger than that in the lowest liquidity shock group (with the exception of the highest-liquidity- shock-highest-surprise group in the case of the 2-year note). Similar results hold for absolute return. Holding the absolute mean surprise constant in each liquidity shock group, the mean absolute return in the highest liquidity shock group is almost always higher than that of the lowest liquidity shock group. The findings suggests that liquidity shocks play an important role in announcement jumps over and above that played by announcement surprises.

We further run a Probit model to control for the roles announcement surprise and liquidity changes play in the frequency of price jumps. We use several more liquidity shock variables to capture the different dimensions of liquidity:

- Standardized shock to hidden depth, $Hidshk^{overall}$, is defined similarly as the depth shock and captures the withdrawal of hidden depth.

- Realized volatility, V_{t-1}, is calculated as square-root of the sum of squared 5-minute log return during the 30-minute interval before the jump. Realized volatility proxies for market uncertainty.

- Order flow OF_{t-1}, is the volume of buy trades minus that of sell trades during the 5-minute interval before jump. As shown in previous literature, order flow carries information of price change. Given that we are interested in whether information embedded in order flow predicts price change but not the direction of price change, we use the absolute value of order flow (scaled by its sample mean).

- Lastly, we examine order imbalance, OB_{t-1}, which is calculated by $depth^{overall}_{ask,t-1} - depth^{overall}_{bid,t-1}$ at the beginning of the 5-minute interval before the jump. Order imbalance is shown to be informative about future price movements both in Cao, Hansch and Wang (2004) and Harris and Panchapagesan (2005). Similar to order flow, we test whether the absolute value order imbalance (scaled by its sample mean) precipitates price jumps.

We first estimate the following model to examine whether liquidity shocks are predictive of jumps

$$
\begin{aligned}
P(jump_t|announcement) \quad = \quad & f(\alpha + \beta_{dpthshk^{overall}} dpthshk^{overall}_{t-1} + \beta_{Hidshk^{overall}} Hidshk^{overall}_{t-1} \\
& + \beta_{sprdshk} sprdshk_{t-1} + \beta_{|OF|}|OF_{t-1}| + \beta_{|OB|}|OB_{t-1}| \\
& + \beta_{vola} V_{t-1}) \qquad (9)
\end{aligned}
$$

where $P(\cdot)$ is probability of a jump, which takes a value of 1 when there is a jump at the announcement time t and 0 when there is no jump at the announcement time.

The first set of columns of Table VII reports the estimates of the above model for the 2-year, 5-year and 10-year notes. The null hypothesis of liquidity variables being jointly zero is rejected for all three maturities. Realized volatility is significant at the 5% level for all maturities, and shocks to overall depth are significant at the 10% level for all maturities. In addition, the shock to spread, $sprdshk$, is significantly positive at the 5% level for the 5-year and 10-year notes. On the other hand, the absolute value of order flow does not significantly precipitate jumps, although they are shown to carry information about future price movement in the previous literature. Overall, liquidity shocks appear to have more predictive power for longer maturity notes.

Next, we estimate a model with only information shocks to examine how well announcement surprises explain jumps

$$P(jump_t|announcement) = f(\alpha + \Sigma_{j=1}^{J}\gamma_j|Sur_{j,t}|) \tag{10}$$

where $|Sur_{j,t}|$ is the absolute value of standardized announcement surprise j. Since we have 30 prescheduled announcements, it is infeasible to include all of them in the estimation. Based on the evidence in Table V, we identify a set of six important announcements: Consumer Price Index, Change in Nonfarm Payrolls, Retail Sales, New Home Sales, ISM index and Initial Jobless Claims as our basic set of announcements. The rest of the announcements are added into the regression one by one, and are kept in the model only if their coefficient is significant. The set of second columns of Table VII reports the estimates of the information shocks model. As gauged by the value of the likelihood function, the model with a pure information shock fairs slightly better than the model with only liquidity shocks, except for the 10-year note where the likelihood function has comparable values.

Finally, we examine the role of both liquidity shocks and information shocks in explaining price jumps. The purpose here is to test whether the information, if there is any, in liquidity shocks is subsumed by the announcement surprise. We estimate the following model with both announcement surprises and liquidity variables as explanatory variables:

$$\begin{aligned} P(jump_t|announcement) &= f(\alpha + \beta_{dpthshk^{overall}} dpthshk_{t-1}^{overall} + \beta_{Hidshk^{overall}} Hidshk_{t-1}^{overall} \\ &\quad + \beta_{sprdshk} sprdshk_{t-1} + \beta_{|OF|}|OF_{t-1}| + \beta_{|OB|}|OB_{t-1}| \\ &\quad + \beta_{vola} V_{t-1} + \Sigma_{j=1}^{J}\gamma_j|Sur_{j,t}|) \end{aligned} \tag{11}$$

where $Sur_{j,t}$ is the standardized announcement surprise which is significant in Equation (10). Estimation results are reported in the third set of columns of Table VII for the 2-year note, 5-year note and 10-year note. Interestingly, adding surprises in macroeconomic news announcements does not reduce the significance of market volatility and shocks to overall depth. The null hypothesis of liquidity variables being jointly zero is again rejected. In other words, whatever the information contained in these variables that is predictive of upcoming jumps is not subsumed by the surprises in macroeconomic news announcements. Overall, the results suggest that jumps are potentially precipitated by higher volatility and withdrawal of liquidity.

B. Post-Jump Price Discovery

In this subsection, we examine the price discovery process after bond prices experience jumps. The literature, e.g., Green (2004), Pasquariello and Vega (2006) and Menveld, Sarkar and van der Wel (2006), compares the impact of order flow on prices on announcement versus non-announcement days. Green (2004) and Menveld, Sarkar and van der Wel (2006) find that order flow is more informative post announcement. The literature, however, is relatively silent on how informative order flow is after a significant large price change. We extend this literature and address the following question: what is the impact of jumps on the price discovery process in the bond market? In particular, do jumps tend to increase or reduce the informativeness of subsequent order flows in the bond market?

We first examine the post-jump price discovery process for all jump days, using non-jumps days as control sample. On jump days, order flows are observed every 5 minutes over the 60-minute interval after the jump. To avoid the effect of multiple jumps, we only include days with single jumps in our analysis[9]. For non-jump days, order flows are observed every 5 minutes during the most active trading period from 8:30 EST to 15:00 EST. The reason of including all observations in the most active period as controls is that the timing of jumps not concurring with announcements is unpredictable. Let $j = 0$ denote the 5-minute interval where jump occurs, the post jump period starts at interval $j = 1$, i.e., the interval right after jumps. We estimate the following model:

$$p_{j+1} - p_j = \alpha + \alpha_{jump} d_{jump} + \beta^{OF} OF_{j+1} + \beta^{OF}_{jump} OF_{j+1} d_{jump} + \varepsilon_{j+1} \tag{12}$$

where p_j denotes the logarithmic mid-quote at the end of interval j, and OF_j is the cumulative order flow calculated from transactions during the interval j. For non-jump days, the observations of bond price and order flows start at 8:30 EST. The dummy variable d_{jump} takes a value of 1 for jump days, and 0 for non-jump days. Thus, the coefficient β^{OF} captures the price impact of order flow during non-jump days, whereas β^{OF}_{jump} essentially captures the post jump price impact of order flow.

Results reported in the first column of Table VIII suggest that β^{OF} is significantly positive for all

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[9] The results are robust when multiple-jumps days are included in the analysis.

three notes, indicating that order flow is positively related to price. This finding is consistent with the previous literature. The coefficient β^{OF}_{jump} is generally negative, suggesting that post-jump order flows have a lesser effect on bond price. However, the coefficient estimate is only significant at the 5% level for the 2-year note. For both 5-year and 10-year notes, the coefficient estimates are highly insignificant. Note that the above results are based on all days with jumps, using non-jump days as control sample. It is likely that there is significant information flow to the market even on days without price jumps. It is also likely that price jumps are triggered by pure liquidity shocks. As a result, simply separating days according to whether there are jumps or not may potentially reduce the power of our analysis.

To sharpen our analysis, we next restrict our analysis only to days with pre-scheduled macroeconomic news announcements. Order flows on announcement days are more likely to carry information regardless whether jumps occur or not. We estimate model (12) using order flows observed on announcement days with price jumps, whereas announcement days without jumps are used as the control sample. To keep the analysis clean, announcement days with jumps occurring away from the announcement time are excluded. To examine the post-jump effect over different time horizons, we estimate the model using order flows observed during the 15-minute, 30-minute and 60-minute time period after jumps.

The results are reported in the second to fourth columns of Table VIII. Similar to the results in the first column, β^{OF} is significantly positive for all three notes. Since we now focus on news announcement days, β^{OF} tends to have a larger magnitude than those in the first column, indicating that order flow has a larger positive effect on price on announcement days. Also similar to the results in the first column, the coefficient β^{OF}_{jump} is negative for all notes. The difference is that the coefficients β^{OF}_{jump} are also statistically significant. This suggests that post-jump order flows on a news announcement day have a significantly smaller effect on bond price than those on a non-jump news announcement day. The results are largely consistent over the 15-minute, 30-minute, and 60-minute post-jump horizons, except that β^{OF}_{jump} decreases in magnitude as time horizon increases from 15-minute to 60-minute. A direct interpretation of the finding is that when jump occurs, information flow contained in the news announcement is incorporated quickly into bond prices. Thus, subsequent order flows tend to have less impact on bond prices. Of course, it is also possible that price discovery slows down after jumps due to lack of trading. However, as reported in Figure 4 we observe a surge in trading volume after jumps. This evidence provides further support that jumps serve as a dramatic form of price discovery by quickly incorporating market information flow into bond prices. On the other hand, when information arrives with a news announcement, smooth prices changes serve as a gradual way of incorporating information into bond prices.

V. Conclusion

We examine price jumps using the data from the limit order book of the U.S. Treasury securities market. Using recently developed statistical tests to identify the location of price jumps, we separate jumps associated with pre-scheduled macroeconomic news announcements from those that are not. Our results show that most of the jumps occur around macroeconomic news announcements. Compared to the existing literature, our study uncovers a more comprehensive list of announcements associated with a significant price change.

Comparing announcements with jumps and announcements without jumps, we find that changes in market characteristics around announcement times are more distinct on announcement days with jumps. Both depth withdraws and spread widens more severely before announcement jumps and trade volume nearly doubles after announcement jumps. We also find that market activities differ between jumps at announcement times and jumps outside of announcement times.

We find that announcement surprise is an imperfect predictor of bond price jumps. Liquidity shocks preceding announcements play an important role in jumps and are in general positively related to the number of jumps and jump size. Finally, looking at the post-jump price discovery process, we find that order flows are in general less informative immediately after announcements with jumps compared to the case where there is no jump at the announcement. The finding suggests that jumps at announcement time help to quickly incorporate information flow into bond prices.

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Appendix A: Jump Test – Bi-Power Variation and "Variance Swap" Approaches

Let the asset price at time $t \in [0, T]$, i.e. S_t, be specified as a general semi-martingale process on the probability space $(\Omega, \mathcal{F}, P)$ with an information filtration $(\mathcal{F}_t) = \{\mathcal{F}_t : t \geq 0\}$:

$$dS_t/S_t = \mu_t dt + \sqrt{V_t} dW_t + (\exp(J_t) - 1)\, dq_t. \tag{13}$$

where μ_t is the instantaneous drift, V_t is the instantaneous variance when there is no random jump, W_t is a standard Brownian motion, q_t is a counting process with finite instantaneous intensity λ_t ($0 \leq \lambda_t < \infty$), and J_t is a non-zero random variable representing the jump in price. Note that the jump diffusion model in Eq. (15) is a very general representation of the asset return process. This is because the demeaned asset price process is a local martingale, it can be decomposed canonically into two orthogonal components, namely a purely continuous martingale and a purely discontinuous martingale, see Theorem 4.18 in Jacod and Shiryaev (2003).

Throughout the paper, we assume that stock prices are observed at regular time intervals $\delta = 1/N$ over a time period. The conventional realized variance (RV) is defined as:

$$RV_N = \sum_{i=1}^{N} r_{\delta,i}^2,$$

where $r_{\delta,j} = \ln(S_{j\delta} - S_{(j-1)\delta})$. It is well known (see, for instance, Jacod and Shiryaev (1987)) that:

$$\operatorname*{plim}_{N\to\infty} RV_N = V_{(0,1)} + \int_0^1 J_u^2 dq_u,$$

where $V_{(0,t)} \equiv \int_0^t V_u du$.

Barndorff-Nielsen and Shephard (2004) introduce a bi-power variation (BPV) measure which is defined in normalized form as:

$$BPV_N = \frac{1}{\mu_1^2} \sum_{i=1}^{N-1} |r_{\delta,i+1}|\, |r_{\delta,i}|\,,$$

where $\mu_p = 2^{p/2}\Gamma((p+1)/2)/\sqrt{\pi}$ for $p > 0$. They show that $\operatorname*{plim}_{N\to\infty} BPV_N = V_{(0,1)}$. Barndorff-Nielsen and Shephard (2006) proposes the following jump test:

$$\frac{V_{(0,1)}\sqrt{N}}{\sqrt{\Omega_{BPV}}} \left(1 - \frac{BPV_N}{RV_N}\right) \xrightarrow{d} \mathcal{N}(0,1). \tag{14}$$

To see the idea of the variance swap jump test, a direct application of Itô's lemma to the price process S_t in Eq. (13)leads to:

$$d\ln S_t = (\mu_t - \lambda_t \eta_t - \frac{1}{2}V_t)dt + \sqrt{V_t} dW_t + J_t dq_t, \tag{15}$$

Taking the difference between Eq. (15) and Eq. (13), and integrating over $[0, T]$, we have:

$$2\int_0^T \left(dS_t/S_t - d\ln S_t\right) = V_{(0,T)} + 2\int_0^T \left(\exp\left(J_t\right) - J_t - 1\right) dq_t. \tag{16}$$

Jiang and Oomen (2007) constructs "variance swap" (SwV) measure which is defined as the discretized version of the left-hand side of Eq. (16), i.e.

$$SwV_M\left(T\right) = 2\sum_{j=1}^{N}\left(R_{\delta,j} - r_{\delta,j}\right) = 2\sum_{j=1}^{N} R_{\delta,j} - 2\ln\left(S_T/S_0\right), \tag{17}$$

where $R_{\delta,j} = (S_{j\delta} - S_{(j-1)\delta})/S_{(j-1)\delta}$. Our empirical analysis is based on the following ratio test:

$$\frac{V_{(0,T)}N}{\sqrt{\Omega_{SwV}}}\left(1 - \frac{RV_M\left(T\right)}{SwV_M\left(T\right)}\right) \xrightarrow{d} \mathcal{N}(0,1) \tag{18}$$

where $\Omega_{SwV} = \frac{1}{9}\mu_6 X_{(0,T)}$ and $X_{(0,T)} = \int_0^T V_u^3 du$. Note that in both BPV and SWV tests, many terms are measured under the null hypothesis of no jumps. As detailed in Jiang and Oomen (2007), consistent and robust estimators of $V_{(0,T)}$ and Ω_{SwV} are obtained from $\widehat{\Omega}_{SwV}^{(p)} = \frac{\mu_6}{9}\frac{N^3\mu_{6/p}^{-p}}{N-p+1}\sum_{j=0}^{N-p}\prod_{k=1}^{p}\left|r_{\delta,j+k}\right|^{6/p}$ for $p \in \{1, 2, \ldots\}$. When both test statistics are significant, we reject the null hypothesis of no jumps, i.e. $H_0 : \lambda_t = 0$ for $t \in [0, T]$. Since we use both BPV and SWV tests at 1% critical level, the hypothesis is rejected if p=max(BPV p-value, SWV p-value)< 0.01. To further take into account of the market microstructure effect, we modify the SWV jump test by allowing measurement error in the observed asset prices, i.e., $\hat{P}_t = P_t + \epsilon_t$ where P_t is the intrinsic price of the asset and ϵ_t is the noise. The standard error of ϵ_t is estimated based on the first-order autocorrelation of the return process. Further details can be found in Jiang and Oomen (2007).

The following procedure is used to identify jump returns. As shown in the simulations, the SWV test generally has higher power, thus jump test in the following procedure refers to the SWV test.

- Step 1: Let $\{r_1, r_2, \cdots r_N\}$ be log return observations during the testing period. If the jump test statistic JS_0 is significant, we record JS_0 and continue to Step 2.

- Step 2: We replace each return observation at interval i, $r_i(i = 1, \cdots, N)$, by the median return of the sample (denoted by r_{md}), and perform jump test on $\{r_1, \cdots, r_{i-1}, r_{md}, r_{i+1}, \cdots, r_N\}$. A series of test statistic $JS^{(i)}, i = 1, 2, \cdots, N$ are recorded.

- Step 3: We compute the differences of the jump test statistic in Step 1 with those in Step 2, i.e., $JS_0 - JS^{(i)}, i = 1, 2, \cdots, N$. Return j is identified as a jump return if $JS_0 - JS^{(j)}$ has the highest value among all returns. This criterion is in the spirit of the likelihood ratio test since r_j is the return that contributes most to the jump test to reject the null hypothesis.

- Step 4: Replace the identified jump, r_j, by the median of returns, and we have a new sample of return observations $\{r_1, \cdots, r_{j-1}, r_{md}, r_{j+1}, \cdots, r_N\}$. Then start over again from Step 1.

The above procedure continues until all jumps are identified. To ensure that identified jump returns are not the result of discrete tick size or bid-ask bounce, we also impose an additional stopping rule that the absolute jump return has to be more than twice the tick size. We find that this restriction virtually has no effect on our identified jump returns.

Appendix B: Monte Carlo Simulations of the Jump Tests

The stochastic volatility jump-diffusion model we consider is:

$$\begin{aligned} dS_t/S_t &= \mu dt + \sqrt{V_t} dW_t^s + J_t dq_t, \\ dV_t &= \beta \left(\alpha - V_t \right) dt + \sigma \sqrt{V_t} dW_t^v, \end{aligned} \tag{19}$$

where $dW_t^s dW_t^v = \rho dt$.

For the parameter values in the benchmark model, we set $\mu = 0, \rho = 0$, α=mean of daily variance of the 2-year note, the value of β is determined by $e^{-\beta}$=first order autocorrelation of daily variance, σ is set from $\frac{\alpha\sigma^2}{2\beta}$=variance of daily return variance. We consider 7 alternative specifications as follows:

Benchmark parameter values: $\mu = 0, \rho = 0$, $\alpha = 0.005$, $\beta = 0.8$, $\sigma = 0.10$

Alternative I parameter values: $\mu = 0, \rho = 0$, $\alpha = 0.005$, $\beta = 0.2$, $\sigma = 0.10$

Alternative II parameter values: $\mu = 0, \rho = 0$, $\alpha = 0.005$, $\beta = 1.6$, $\sigma = 0.10$

Alternative III parameter values: $\mu = 0, \rho = 0$, $\alpha = 0.005$, $\beta = 0.8$, $\sigma = 0.05$

Alternative IV parameter values: $\mu = 0, \rho = 0$, $\alpha = 0.005$, $\beta = 0.8$, $\sigma = 0.20$

Alternative V parameter values: $\mu = 0, \rho = 0.50$, $\alpha = 0.005$, $\beta = 0.8$, $\sigma = 0.10$

Alternative VI parameter values: $\mu = 0, \rho = -0.50$, $\alpha = 0.005$, $\beta = 0.8$, $\sigma = 0.10$

Each ”day” we simulate a sample path of the process in (19) using the Euler scheme with 1 minute discretization interval over a total of 9.5 hours. Then we sample returns at 5-minute interval. Jumps (J) are added to the 10th, 20th, and 30th observations of 5-minute returns. To examine size, we set J=0. To examine power we set $J = 4 \times \sqrt{\alpha}, 7 \times \sqrt{\alpha}, 10 \times \sqrt{\alpha}$. Jump tests are performed on the 5-minute return observations. The procedure is repeated 10,000 times. Simulation results are summarized in the following table:

Table A: Size and Power of Jump Tests (%)

		Scenarios						
Jump Size	Jump Test	Benchmark	A1	A2	A3	A4	A5	A6
$0 \times \sqrt{\alpha}$	BPV	3.4	3.01	2.8	2.75	4.13	3.3	3.18
	SwV	4.65	4.5	4.34	2.99	6.34	4.44	4.13
	Joint	0.75	0.72	0.48	0.32	1.29	0.62	0.57
$4 \times \sqrt{\alpha}$	BPV	54.25	55.27	51.62	49.49	53.17	53.9	53.9
	SwV	73.65	72.21	75.5	82.81	63.49	75.46	72.9
	Joint	51.12	52.49	48.58	46.87	48.97	51.38	50.49
$7 \times \sqrt{\alpha}$	BPV	93.72	90.97	94.42	97.23	85.45	92.45	92.99
	SwV	99.13	98.4	99.72	99.96	93.21	99.49	98.65
	Joint	93.56	90.65	94.4	97.22	84.36	92.39	92.71
$10 \times \sqrt{\alpha}$	BPV	99.42	98.98	99.7	99.92	95.97	99.41	99.43
	SwV	100	99.97	100	100	99.14	100	99.98
	Joint	99.42	98.96	99.7	99.92	95.81	99.41	99.42

Table I. Summary Statistics of Market Activities

This table reports the summary statistics of daily trading volume ($ billions), daily return volatility (%) calculated from 5-minute returns based on the mid bid-ask quote, trade durations (seconds), relative spread ($\times 10,000$) and spread in ticks, average depth at the best bid/ask ($ millions), average depth in the entire order book ($ millions), average hidden depth at the best bid/ask ($ millions), and average hidden depth in the entire book during the sample period from 2005 to 2006. Spread and depth variables are averaged over 5-minute interval of the trading day.

Variable	Mean	Median	StDev	Max	Min	Skewness	Kurtosis
Panel A: 2-year note)							
Spread (in ticks)	1.06	1.05	0.05	1.59	0.99	4.50	39.24
Relative spread ($\times 10,000$)	0.83	0.83	0.04	1.29	0.78	5.02	47.35
Trading volume ($ billions)	27.45	26.55	10.12	79.50	6.05	0.97	5.08
Trading durations (seconds)	15.99	14.61	6.76	48.21	3.48	0.98	4.09
Return volatility (%)	0.07	0.06	0.03	0.28	0.03	2.61	13.60
Depth at the best bid and ask ($ mil)	637.72	593.14	254.17	1567.41	190.25	0.44	2.46
Hidden depth at the best bid and ask($mil)	32.64	25.77	22.56	173.68	1.82	2.04	10.21
Depth of the entire order book ($ mil)	5122.56	4227.90	2416.23	10305.34	899.38	0.34	1.77
Hidden depth of the entire order book ($ mil)	99.83	81.71	73.53	526.09	9.25	2.04	9.08
Panel B: 3-year note							
Spread (in ticks)	1.19	1.17	0.10	1.90	1.04	2.17	10.88
Relative spread ($\times 10,000$)	0.94	0.92	0.08	1.50	0.82	2.12	10.47
Trading volume ($ billions)	9.60	9.05	3.65	22.92	1.70	0.72	3.34
Trading durations (seconds)	27.47	21.73	16.76	104.33	6.13	1.52	5.18
Return volatility (%)	0.10	0.09	0.04	0.33	0.04	2.24	9.44
Depth at the best bid and ask ($ mil)	167.49	164.22	75.12	406.70	39.24	0.31	2.27
Hidden depth at the best bid and ask($mil)	8.83	6.66	8.46	111.75	0.08	4.86	49.94
Depth of the entire order book ($ mil)	1260.76	1025.58	686.90	3141.09	198.15	0.57	2.06
Hidden depth of the entire order book ($ mil)	29.01	18.33	30.73	272.72	0.61	3.46	21.20
Panel C: 5-year note							
Spread (in ticks)	1.18	1.16	0.10	2.30	1.04	4.65	42.55
Relative spread ($\times 10,000$)	0.93	0.92	0.08	1.87	0.83	4.93	47.01
Trading volume ($ billions)	24.69	24.17	7.48	50.31	7.71	0.55	3.36
Trading durations (seconds)	6.74	6.02	3.13	23.94	2.20	1.41	5.97
Return volatility (%)	0.17	0.15	0.06	0.45	0.07	1.71	6.90
Depth at the best bid and ask ($ mil)	119.30	118.22	33.46	213.12	54.86	0.47	2.71
Hidden depth at the best bid and ask($mil)	6.83	5.90	4.25	39.37	0.22	1.90	10.92
Depth of the entire order book ($ mil)	1238.48	1154.73	485.39	2522.77	442.96	0.43	2.01
Hidden depth of the entire order book ($ mil)	40.36	29.48	133.01	2885.68	4.18	20.66	441.77

Variable	Mean	Median	StDev	Max	Min	Skewness	Kurtosis
Panel D: 10-year note							
Spread (in ticks)	1.13	1.11	0.07	1.82	0.99	3.27	28.19
Relative spread ($\times 10,000$)	1.79	1.77	0.11	2.93	1.60	3.16	25.69
Trading volume ($ billions)	22.76	22.62	6.93	43.68	5.32	0.38	2.84
Trading durations (seconds)	6.59	5.59	3.35	22.49	2.23	1.32	4.82
Return volatility (%)	0.29	0.26	0.10	0.77	0.11	1.67	7.43
Depth at the best bid and ask ($ mil)	120.93	118.37	32.11	227.99	50.96	0.55	3.10
Hidden depth at the best bid and ask($mil)	5.50	4.82	3.24	28.60	0.88	2.12	11.88
Depth of the entire order book ($ mil)	1520.08	1376.26	657.52	3459.07	439.77	0.75	2.69
Hidden depth of the entire order book ($ mil)	36.43	31.22	24.07	233.61	2.52	2.88	20.97
Panel E: 30-year bond							
Spread (in ticks)	2.05	2.02	0.37	6.47	1.48	3.80	43.37
Relative spread ($\times 10,000$)	3.10	3.02	0.46	9.23	2.41	5.23	64.89
Trading volume ($ billions)	2.72	2.52	1.08	8.42	0.87	1.00	4.52
Trading durations (seconds)	52.97	27.59	67.33	612.96	8.88	3.55	19.01
Return volatility (%)	0.53	0.50	0.23	4.26	0.23	8.77	135.06
Depth at the best bid and ask ($ mil)	11.96	11.54	2.41	21.75	6.15	0.68	3.45
Hidden depth at the best bid and ask($mil)	1.14	0.92	1.01	11.31	0.03	4.56	38.50
Depth of the entire order book ($ mil)	133.42	118.88	52.45	312.63	46.50	1.45	4.58
Hidden depth of the entire order book ($ mil)	6.29	4.84	5.91	51.60	0.15	2.98	16.65

Table II. Macroeconomic News with Pre-Scheduled Announcements

This table reports the list of macroeconomic news included in our analysis. N denotes the total number of announcements during the period from January 2005 to December 2006. Day and Time denote, respectively, the weekday (or day of the month) and time (EST) of announcement. σ_{surprise} denotes the standard deviation of survey surprises. $N_{|\text{surprise}|>k\sigma}$ denotes the number of announcements where the survey surprise is more than k standard deviation.

Event	N	Day	Time	σ_{surprise}	$N_{\|\text{surprise}\|>\sigma}$	$N_{\|\text{surprise}\|>2\sigma}$
Business Inventories	24	Around the 15th of the month	8:30[a]	0.002	5	1
Capacity Utilization	24	Two weeks after month end	9:15	0.003	6	1
Change in Nonfarm Payrolls	24	First Friday of the month	8:30	59.228	9	0
Chicago PMI	24	Last business day of the month	10:00	5.094	8	1
Construction Spending	24	Two weeks after month-end	10:00	0.245	1	1
Consumer Confidence	24	Last Tuesday of Month	10:00	3.860	6	2
Consumer Credit	24	5th business day of the month	15:00	125.82	1	1
Consumer Price Index	24	Around the 13th of the month	8:30	0.002	9	0
Current Account	8	10 to 11 weeks after quarter-end	8:30	7.687	2	0
Durable Orders	24	Around the 26th of the month	8:30	0.031	9	1
Economic outlook	6	According to schedule	10:00[b]	n.a.	n.a.	n.a.
Existing Home Sales	24	On the 25th of the month	10:00	0.160	7	1
FOMC Minutes	16	Thursday following the next FOMC meeting date	14:00	n.a.	n.a.	n.a.
FOMC rate decision expected	16	According to schedule	14:10	0.000	0	0
Factory Orders	24	Around the first business day of the month	10:00	0.006	6	2
GDP Advance	8	3rd / 4th week of the month for prior quarter	8:30	0.006	1	1
GDP Final	8	3rd / 4th week of second month following the quarter	8:30	0.001	4	1
GDP Preliminary	8	3rd / 4th week of first month following the quarter	8:30	0.003	3	0
Housing Starts	24	Two or three weeks after the reporting month	8:30	124.26	6	2

Event	N	Day	Time	σ_{surprise}	$N_{\lvert\text{surprise}\rvert>\sigma}$	$N_{\lvert\text{surprise}\rvert>2\sigma}$
ISM Services	24	On the third business day of the month	10:00	2.834	9	1
ISM index	24	First business day of the month	10:00	2.332	6	1
Industrial Production	24	Around the 15th of the month	9:15	0.003	8	1
Initial Jobless Claims	104	Thursday weekly	8:30	17.499	23	6
Leading Indicators	24	around the first few business days of the month	8:30	0.002	7	2
Monthly Treasury Budget	24	about the third week of the month	14:00	5.239	4	2
NY Empire State Index	24	15th/16th of the month	8:30	9.738	9	1
New Home Sales	24	Around the last business day of the month	10:00	92.492	6	2
PCE	24	Around the first business day of the month	8:30	0.046	5	5
Personal Income	24	Around the first business day of the month	8:30	0.003	2	1
Philadelphia Fed	24	Third Thursday of the month	12:00	7.960	10	0
Producer Price Index	24	Around the 11th of each month	8:30	0.307	2	1
Retail Sales	24	Around the 12th of the month	8:30	0.121	1	1
Semiannual Monetary Policy Report	4	February and July annually	10:00[c]	n.a.	n.a.	n.a.
Trade Balance	24	Around the 20th of the month	8:30	3.225	7	1
ADP National Employment Report	8	2 days before Change in Nonfarm Payrolls	8:15	n.a.	n.a.	n.a.

[a] – The announcement of Business Inventories took place at 8:30 AM for 16 days during our sample period

[b] – The announcement of FOMC Rate Decision also happens at 14:13 PM, 14:15 PM, 14:16 PM, and 14:19 PM in our sample period according to Bloomberg.

[c] – The announcement also happens at 14:30 PM.

Table III. Summary Statistics of Bond Price Jumps

This table, Panel A, reports the number of days identified as having jumps (N_d), the number of jumps (N) and summary statistics of jump size, including the mean, absolute mean, absolute median, maximum, minimum, standard deviation ($StdDev$), skewness and kurtosis. Panel B reports the number of concurrent jumps across maturities, where jumps of two different maturities occurring at the same or adjacent 5-minute interval are referred to as overlapping jumps.

Bond	N_d	N	Mean	Mean (abs.)	Median (abs.)	Max	Min	StdDev	Skewness	Kurtosis
Panel A: All Jumps										
2-year note	60	69	0.00	0.08	0.07	0.24	-0.17	0.09	0.44	2.69
3-year note	66	74	0.01	0.12	0.11	0.28	-0.28	0.14	-0.21	2.00
5-year note	65	72	-0.01	0.16	0.14	0.40	-0.41	0.18	0.17	2.12
10-year note	58	63	-0.01	0.28	0.24	0.70	-0.64	0.31	-0.02	2.04
30-year bond	69	76	-0.09	0.50	0.40	2.13	-3.55	0.67	-1.20	11.69
Panel B: Positive Jumps										
2-year note	31	32	0.08	0.08	0.06	0.24	0.04	0.05	1.71	5.57
3-year note	40	41	0.12	0.12	0.11	0.28	0.05	0.05	1.06	3.59
5-year note	30	31	0.17	0.17	0.15	0.40	0.08	0.08	1.11	3.79
10-year note	31	32	0.27	0.27	0.24	0.70	0.15	0.12	1.71	5.85
30-year bond	30	30	0.52	0.52	0.41	2.13	0.24	0.36	2.94	13.36
Panel C: Negative Jumps										
2-year note	34	37	-0.07	0.07	0.07	-0.04	-0.17	0.03	-1.22	3.78
3-year note	31	33	-0.12	0.12	0.10	-0.06	-0.28	0.06	-1.11	3.28
5-year note	37	41	-0.16	0.16	0.13	-0.09	-0.41	0.08	-1.47	4.92
10-year note	28	31	-0.29	0.29	0.24	-0.16	-0.64	0.13	-1.47	4.55
30-year bond	43	46	-0.49	0.49	0.37	-0.21	-3.55	0.50	-5.11	31.59

	2-year note	3-year note	5-year note	10-year note	30-year bond
Panel D: Concurrent jumps across maturities					
2-year note	69				
3-year note	48	74			
5-year note	43	50	72		
10-year note	36	42	44	63	
30-year bond	30	33	39	47	76

Table IV. Jumps and Pre-Scheduled News Announcements

This table, Panels A and B, reports the number of jumps, N, and summary statistics of jumps associated with a pre-scheduled news announcement and those not directly associated with a pre-scheduled news announcement. A jump is referred to as associated with a news announcement if the 5-minute jump interval overlaps with the 10-minute window centered around the announcement time. The summary statistics include the mean, absolute mean, absolute median, maximum, minimum, standard deviation ($StdDev$), skewness and kurtosis. Panels C and D report the number of concurrent jumps across maturities, where overlapping jumps are defined in the same way as in Table III.

Bond	N	Mean	Mean (abs.)	Median (abs.)	Max	Min	StdDev	Skewness	Kurtosis
Panel A: Jumps Associated with Pre-Scheduled Announcement									
2-year note	63	0.00	0.08	0.07	0.24	-0.17	0.09	0.45	2.62
3-year note	70	0.01	0.13	0.11	0.28	-0.28	0.14	-0.22	1.99
5-year note	65	-0.01	0.17	0.14	0.40	-0.41	0.19	0.08	2.03
10-year note	58	-0.01	0.28	0.24	0.70	-0.64	0.31	0.00	2.05
30-year bond	59	-0.07	0.47	0.42	0.94	-1.01	0.51	0.28	1.89
Panel B: Jumps Not Associated with Pre-Scheduled Announcement									
2-year note	6	0.00	0.05	0.05	0.07	-0.07	0.05	0.02	1.19
3-year note	4	0.01	0.09	0.09	0.12	-0.09	0.09	0.05	1.07
5-year note	7	-0.06	0.11	0.10	0.18	-0.12	0.10	1.98	5.04
10-year note	5	0.00	0.24	0.24	0.26	-0.35	0.25	-0.41	1.33
30-year bond	17	-0.16	0.61	0.27	2.13	-3.55	1.04	-1.36	8.04

	2-year note	3-year note	5-year note	10-year note	30-year bond
Panel C: Concurrent Jumps Associated with Pre-Scheduled Announcement					
2-year note	63				
3-year note	46	70			
5-year note	41	47	65		
10-year note	35	41	42	58	
30-year bond	29	32	37	41	59
Panel D: Concurrent Jumps Not Associated with Pre-Scheduled Announcement					
2-year note	6				
3-year note	2	4			
5-year note	2	3	7		
10-year note	1	1	2	5	
30-year bond	1	1	2	6	17

Table V. Jumps and News Announcement Surprises

Panel A reports the top 15 news announcements with the largest number of concurrent jumps. It reports the number of jumps and mean absolute jump returns associated with each macroeconomic news. N_J is the number of jumps on 2-, 3-, 5-, 10- and 30-year bond prices. Total N_J is the number of unique jumps (excluding concurrent jumps) among all maturities. $|ret_j|$ denotes the mean absolute jump return. $|sur|$ denotes the mean absolute surprise. Panel B reports the mean absolute jump return, $|ret_j|$, mean absolute surprise $|sur|$ and the number of jumps occurs with significant surprise, N^*_J, of each of the 5 jump groups sorted according to absolute jump return.

Panel A	2-year note		3-year note		5-year note		10-year note		30-year bond		
News	N_j	$\|ret_j\|$	N_j	$\|ret_j\|$	N_j	$\|ret_j\|$	N_j	$\|ret_j\|$	N_j	$\|ret_j\|$	Total N_j
Initial Jobless Claims	9	0.054	7	0.097	7	0.151	7	0.233	6	0.438	15
Consumer Price Index	13	0.073	11	0.146	8	0.195	11	0.319	9	0.540	15
Change in Nonfarm Payrolls	10	0.122	13	0.186	9	0.284	11	0.380	6	0.771	14
Retail Sales	9	0.070	8	0.111	6	0.174	7	0.255	5	0.456	12
Producer Price Index	3	0.065	5	0.102	6	0.167	4	0.324	6	0.493	8
ISM index	1	0.062	4	0.082	4	0.127	4	0.206	6	0.342	8
Construction Spending	1	0.062	4	0.082	4	0.127	4	0.206	6	0.342	8
Durable Orders	3	0.064	3	0.120	5	0.159	2	0.373	4	0.521	7
New Home Sales	4	0.047	2	0.069	4	0.110	2	0.216	3	0.348	6
Housing Starts	3	0.063	4	0.134	4	0.152	1	0.405	2	0.620	6
FOMC rate decision expected	4	0.088	4	0.125	0		1	0.240	3	0.491	6
Consumer Confidence	3	0.047	0		3	0.104	3	0.235	5	0.388	6
NY Empire State Index	4	0.043	4	0.094	5	0.158	5	0.225	4	0.457	5
FOMC Minutes	4	0.098	3	0.153	4	0.182	3	0.280	0		5
GDP Advance	1	0.106	3	0.099	3	0.135	3	0.245	3	0.445	4

Panel B	2-year note			3-year note			5-year note			10-year note			30-year bond		
	$\|ret_j\|$	$\|Sur\|$	N^*_j	$\|ret_j\|$	$\|Sur\|$	N^*_j	$\|ret_j\|$	$\|Sur\|$	N^*_j	$\|ret_j\|$	$\|Sur\|$	N^*_j	$\|ret_j\|$	$\|Sur\|$	N^*_j
1 (lowest)	0.037	1.005	5	0.063	0.746	3	0.090	1.058	4	0.166	0.722	3	0.245	0.880	4
2	0.047	0.976	4	0.078	1.236	5	0.110	1.154	4	0.203	1.108	4	0.308	0.837	4
3	0.059	1.055	3	0.103	0.871	4	0.139	0.923	5	0.247	1.247	5	0.402	1.044	4
4	0.076	0.942	4	0.143	0.693	2	0.192	0.963	3	0.314	0.651	2	0.533	1.101	3
5 (highest)	0.142	0.846	4	0.226	0.972	6	0.280	0.793	5	0.501	1.043	5	0.795	1.144	8

Table VI. Jumps, News Announcement Surprises, and Liquidity Shocks

This table reports how jumps are related to liquidity shocks and announcement surprises. Panel A reports findings associated with shocks in overall depth, $depshk$ and Panel B reports findings associated with shocks in spread, $sprdshk$. We first sort announcements according to their liquidity shocks in the previous 5-minute interval into 3 groups, with 1 indicating the lowest liquidity shocks and 3 indicating the highest liquidity shocks. Within each group, we further sort announcements into 3 sub-groups according to their absolute announcement surprise $|sur|$. In the table, $|ret|$ denotes the mean absolute return. $|sur|$ denotes the mean absolute surprise. N_j denotes the number of jumps.

Panel A	2-year note				3year note				5-year note				10-year note				30-year bond			
$depshk$	$depshk$	$\|sur\|$	$\|ret\|$	N_j	$depshk$	$\|sur\|$	$\|ret\|$	N_j	$depshk$	$\|sur\|$	$\|ret\|$	N_j	$depshk$	$\|sur\|$	$\|ret\|$	N_j	$depshk$	$\|sur\|$	$\|ret\|$	N_j
1(low)	0.739	0.168	0.012	1	0.576	0.190	0.023	3	0.898	0.176	0.035	3	0.852	0.192	0.056	0	0.748	0.198	0.082	2
	0.694	0.647	0.023	3	0.538	0.653	0.039	5	0.841	0.629	0.059	5	0.832	0.685	0.069	1	0.768	0.702	0.124	2
	0.695	1.635	0.030	6	0.502	1.574	0.039	6	0.762	1.531	0.063	4	0.863	1.728	0.099	4	0.793	1.759	0.160	5
2	1.412	0.193	0.014	1	1.467	0.184	0.021	0	1.631	0.203	0.034	1	1.484	0.203	0.056	5	1.298	0.171	0.140	3
	1.441	0.682	0.017	3	1.392	0.749	0.023	2	1.618	0.720	0.045	4	1.484	0.654	0.086	5	1.357	0.641	0.151	6
	1.424	1.751	0.023	7	1.465	1.794	0.033	5	1.646	1.792	0.061	6	1.500	1.541	0.089	5	1.363	1.573	0.195	8
3 (high)	2.872	0.176	0.026	8	2.797	0.159	0.035	7	3.045	0.162	0.058	8	2.748	0.140	0.087	5	2.654	0.171	0.132	6
	2.899	0.653	0.028	7	2.767	0.583	0.042	8	3.055	0.657	0.069	11	2.744	0.623	0.106	8	2.447	0.641	0.178	6
	2.747	1.421	0.029	5	2.775	1.402	0.051	10	2.952	1.495	0.072	8	2.795	1.524	0.133	13	2.354	1.459	0.184	9
Panel B	2-year note				3year note				5-year note				10-year note				30-year bond			
$sprdshk$	$sprdshk$	$\|sur\|$	$\|ret\|$	N_j	$sprdshk$	$\|sur\|$	$\|ret\|$	N_j	$sprdshk$	$\|sur\|$	$\|ret\|$	N_j	$sprdshk$	$\|sur\|$	$\|ret\|$	N_j	$sprdshk$	$\|sur\|$	$\|ret\|$	N_j
1(low)	0.253	0.168	0.012	1	0.242	0.190	0.023	3	0.238	0.176	0.035	3	0.522	0.192	0.056	0	0.443	0.198	0.082	2
	0.469	0.647	0.023	3	0.593	0.653	0.039	5	0.488	0.629	0.059	5	0.532	0.685	0.069	1	0.573	0.702	0.124	2
	0.508	1.635	0.030	6	0.644	1.574	0.039	6	0.523	1.531	0.063	4	0.446	1.728	0.099	4	0.582	1.759	0.160	5
2	0.162	0.193	0.014	1	0.468	0.184	0.021	0	0.258	0.203	0.034	1	0.259	0.203	0.056	5	1.030	0.171	0.140	3
	0.141	0.682	0.017	3	0.280	0.749	0.023	2	0.312	0.720	0.045	4	0.234	0.654	0.086	5	0.506	0.641	0.151	6
	0.169	1.751	0.023	7	0.386	1.794	0.033	5	0.461	1.792	0.061	6	0.381	1.541	0.089	5	0.941	1.573	0.195	8
3(high)	0.336	0.176	0.026	8	0.372	0.159	0.035	7	0.272	0.162	0.058	8	0.301	0.140	0.087	5	0.826	0.171	0.132	6
	0.344	0.653	0.028	7	0.496	0.583	0.042	8	0.389	0.657	0.069	11	0.305	0.623	0.106	8	0.639	0.641	0.178	6
	0.361	1.421	0.029	5	0.373	1.402	0.051	10	0.443	1.495	0.072	8	0.384	1.524	0.133	13	0.590	1.459	0.184	9

Table VII. Jumps, Information Shocks and Liquidity Shocks

This table reports the estimation results of the probit model of bond price jumps at the time of a pre-scheduled news announcement. The explanatory variables include return volatility ($volatility$), spread shock($sprdshk$), absolute order flow (OF), absolute order imbalance(OB), overall depth shock ($dpthshk^{overall}$), overall hidden depth shock ($Hidshk^{overall}$) and surprises in news announcement.

	Liquidity Shocks: Eqn 9			Information Shocks: Eqn 10			Information vs. Liquidity Shocks: Eqn 11		
	Estimate	Standard Error	P-Value	Estimate	Standard Error	P-Value	Estimate	Standard Error	P-Value
Panel A: 2-year note									
Intercept	-1.811	0.307	<.0001	-1.300	0.196	<.0001	-2.508	0.444	<.0001
Volatility	1.902	0.864	0.028				2.346	0.956	0.014
sprdshk	0.132	0.121	0.277				0.227	0.156	0.146
OF	0.165	0.123	0.181				0.207	0.135	0.126
OB	-0.135	0.127	0.288				-0.007	0.138	0.959
dpthshk^{overall}	-0.433	0.232	0.063				-0.500	0.276	0.070
hidshk^{overall}	0.127	0.147	0.385				0.265	0.171	0.120
Consumer Price Index				0.889	0.311	0.004	0.928	0.321	0.004
Initial Jobless Claims				-0.092	0.245	0.707	0.150	0.284	0.598
ISM index				-0.290	0.578	0.616	-0.449	0.680	0.509
Change in Nonfarm Payrolls				0.267	0.436	0.541	-0.027	0.548	0.960
Retail Sales				12.982	6.957	0.062	20.912	7.827	0.008
New Home Sales				0.470	0.376	0.211	0.758	0.422	0.072
Likelihood	-67.685			-64.916			-56.404		
Joint test: $beta_{liquidty} = 0$	13.290		0.04				17.024		0.010

	Liquidity Shocks: Eqn 9			Information Shocks: Eqn 10			Information vs. Liquidity Shocks: Eqn 11		
	Estimate	Standard Error	P-Value	Estimate	Standard Error	P-Value	Estimate	Standard Error	P-Value
Panel B: 5-year note									
Intercept	-1.766	0.350	$<.0001$	-1.259	0.187	$<.0001$	-2.473	0.492	$<.0001$
Volatility	0.852	0.282	0.003				1.254	0.329	0.000
sprdshk	0.210	0.107	0.050				0.139	0.157	0.375
OF	0.003	0.121	0.977				-0.369	0.194	0.057
OB	-0.041	0.149	0.782				-0.076	0.170	0.656
dpthshk^{overall}	-0.416	0.227	0.067				-0.929	0.287	0.001
hidshk^{overall}	0.056	0.127	0.656				0.101	0.149	0.498
Consumer Price Index				0.043	0.380	0.909	-0.015	0.467	0.974
Initial Jobless Claims				-0.004	0.206	0.985	0.119	0.230	0.604
ISM index				0.634	0.335	0.058	0.684	0.358	0.056
Change in Nonfarm Payrolls				0.897	0.334	0.007	1.207	0.448	0.007
Retail Sales				9.935	7.183	0.167	14.742	8.117	0.069
New Home Sales				0.103	0.435	0.814	0.505	0.479	0.292
Likelihood	-74.270			-72.258			-59.832		
Joint $beta_{liquidty} = 0$	14.760		0.03				24.853		0.0004
Panel C: 10-year note									
Intercept	-1.731	0.332	$<.0001$	-1.373	0.194	$<.0001$	-2.635	0.472	$<.0001$
Volatility	0.788	0.159	$<.0001$				0.838	0.178	$<.0001$
sprdshk	0.250	0.118	0.034				0.160	0.168	0.340
OF	0.007	0.161	0.968				0.029	0.190	0.881
OB	-0.382	0.176	0.030				-0.445	0.221	0.044
dpthshk^{overall}	-0.457	0.235	0.052				-0.818	0.300	0.006
hidshk^{overall}	0.031	0.121	0.798				0.021	0.141	0.880
Consumer Price Index				0.678	0.305	0.026	0.460	0.365	0.208
Initial Jobless Claims				-0.106	0.242	0.662	0.114	0.261	0.664
ISM index				0.721	0.345	0.037	0.907	0.422	0.031
Change in Nonfarm Payrolls				1.085	0.324	0.001	1.017	0.462	0.028
Retail Sales				19.091	7.349	0.009	21.637	7.937	0.006
New Home Sales				0.462	0.312	0.138	0.551	0.353	0.118
Likelihood	-69.883			-70.679			-53.672		
Joint $beta_{liquidty} = 0$	37.560		0.0001				34.014		0.0001

Table VIII. Post-Jump Price Discovery: Order Flow

This table reports the coefficient estimates, standard errors and p-values for the post-jump price discovery process specified in (12).

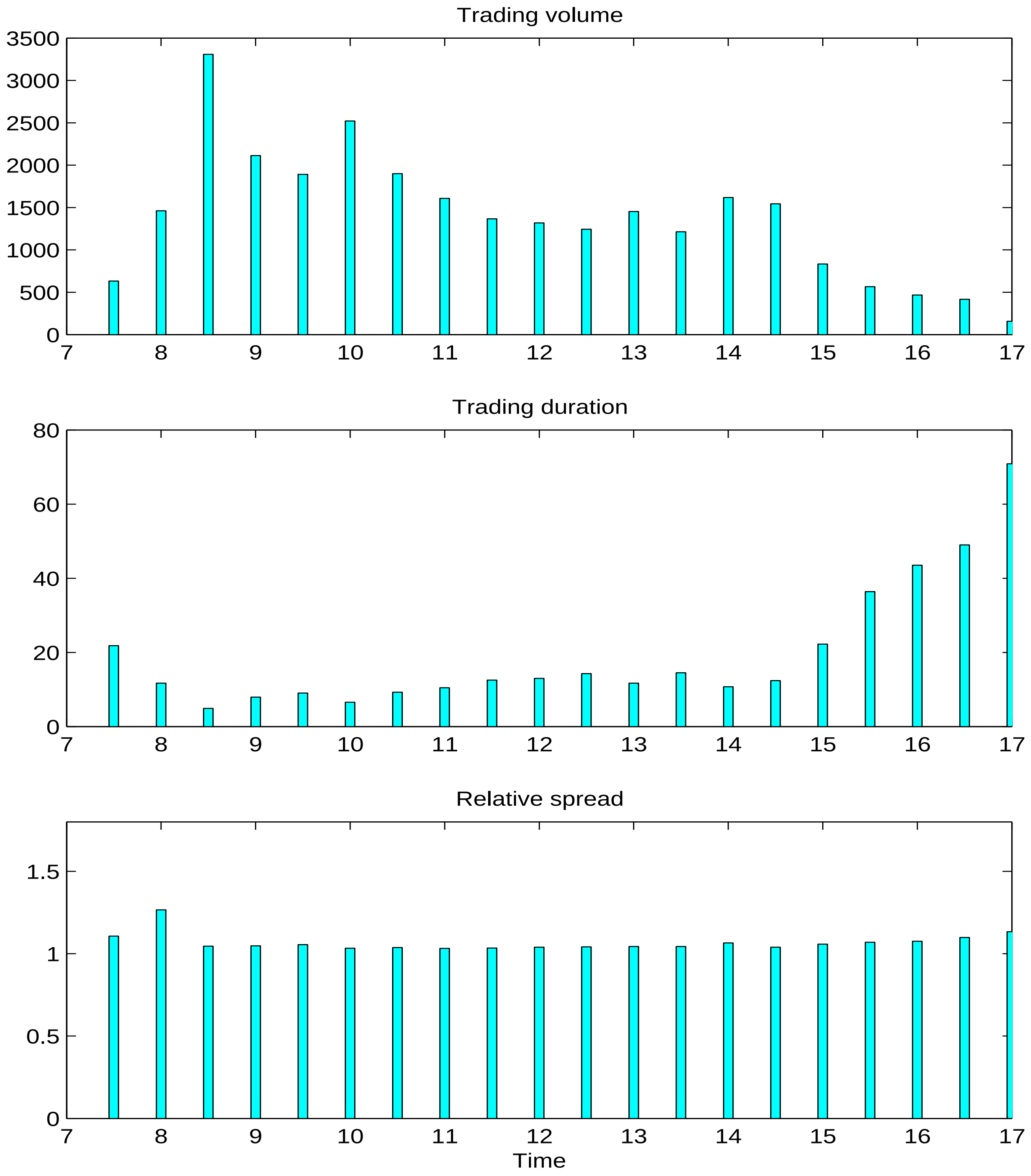
$$p_{j+1} - p_j = \alpha + \alpha_{jump} d_{jump} + \beta^{OF} x_{j+1} + \beta^{OF}_{jump} x_{j+1} d_{jump} + \varepsilon_{j+1}$$

The first set of columns contrasts the price discovery process after jumps vs. days with no jumps. For jump days, the order flows (OF) are observed every 5-minute over the 60-minute horizon after jumps. For non-jump days, the order flows (OF) are observed every 5-minute from 8:30 to 15:00 EST. The second, third and fourth set of columns restrict our analysis to the days with pre-scheduled news announcements and contrasts the price discovery process after jumps vs. days with no jumps. The model is estimated over 15-minute, 30-minute, and 60-minute horizon after jumps. Results for 2-year note, 5-year note, and 10-year note are reported in Panels A, B, and C respectively.

	All: Jump vs. No Jump			News: Jump vs. No Jump (15m)			News: Jump vs. No Jump (30m)			News: Jump vs. No Jump (60m)		
	Estimate	Std Error	P-value	Estimate	Std Error	P-value	Estimate	Std Error	P-value	Estimate	Std Error	P-value
Panel A: 2-year note												
α	0.040	0.036	0.272	0.223	0.540	0.680	0.032	0.315	0.920	0.214	0.183	0.242
α_{jump}	-0.943	0.256	0.000	-0.002	1.277	0.999	-0.497	0.731	0.497	-0.250	0.416	0.549
β^{OF}	0.014	0.000	<.0001	0.019	0.002	<.0001	0.018	0.001	<.0001	0.016	0.001	<.0001
β^{OF}_{jump}	-0.002	0.001	0.008	-0.007	0.003	0.016	-0.005	0.002	0.013	-0.004	0.001	0.002
$adj-R^2$	0.189			0.124			0.145			0.151		
Panel B: 5-year note												
α	0.506	0.080	<.0001	0.474	0.926	0.609	0.447	0.568	0.431	0.685	0.342	0.045
α_{jump}	0.683	0.570	0.234	3.045	2.255	0.177	0.947	1.387	0.495	1.351	0.835	0.106
β^{OF}	0.060	0.001	<.0001	0.081	0.005	<.0001	0.079	0.003	<.0001	0.070	0.002	<.0001
β^{OF}_{jump}	-0.002	0.001	0.179	-0.035	0.010	0.000	-0.026	0.006	<.0001	-0.018	0.004	<.0001
$adj-R^2$	0.227			0.230			0.250			0.244		
Panel C: 10-year note												
α	0.459	0.133	0.001	0.837	1.433	0.559	0.221	0.909	0.808	0.710	0.567	0.211
α_{jump}	0.545	0.941	0.562	-1.049	3.696	0.777	-0.325	2.351	0.890	0.196	1.466	0.894
β^{OF}	0.128	0.001	<.0001	0.178	0.008	<.0001	0.160	0.006	<.0001	0.134	0.004	<.0001
β^{OF}_{jump}	-0.004	0.003	0.146	-0.065	0.018	0.001	-0.038	0.012	0.002	-0.018	0.008	0.022
$adj-R^2$	0.288			0.341			0.324			0.292		

FIGURE 1
Intraday Market Activities

This figure plots market activities in each half-hour window during the day from 7:30 to 17:00. Variables include trading volume ($ millions), trading duration (seconds), relative bid-ask spread ($\times 10,000$), return volatility (%) calculated from 5-minute returns based on the mid bid-ask quote, average depth at the best bid/ask ($ millions) calculated over each 5-minute interval, and average hidden depth at the best bid/ask ($ millions) calculated over each 5-minute interval.



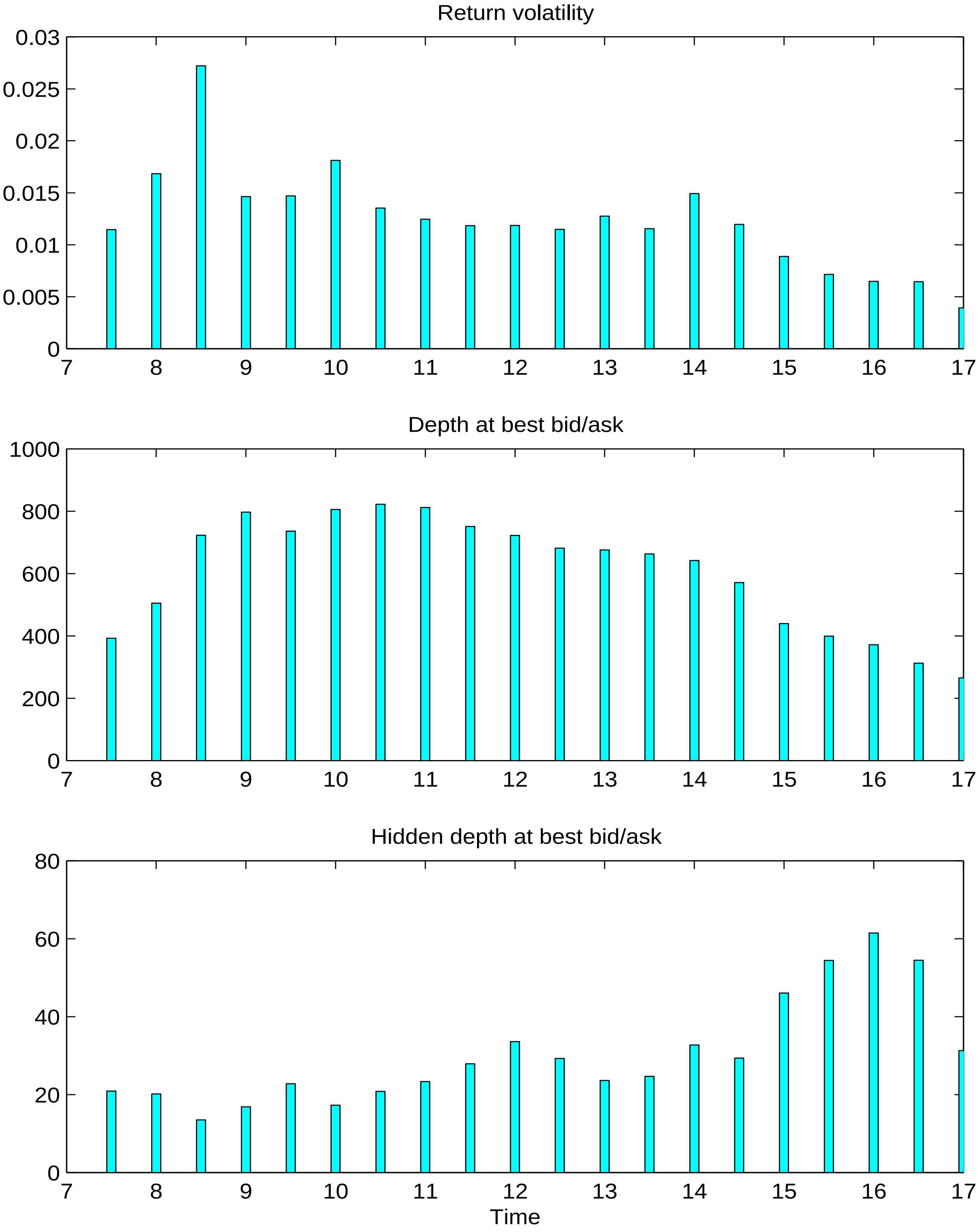

Return volatility
0.03
0.025
0.02
0.015
0.01
0.005
0
7
8
9
10
11
12
13
14
15
16
17
Depth at best bid/ask
1000
800
600
400
200
0
7
8
9
10
11
12
13
14
15
16
17
Hidden depth at best bid/ask
80
60
40
20
0
7
8
9
10
11
12
13
14
15
16
17
Time

FIGURE 2

Intraday Distribution of Jump Time

This figure plots intra-day distribution of jump frequency, where the number of jumps is calculated over 5-minute time interval. The intra-day distribution of jump frequency is plotted for all jumps as well as jumps outside pre-scheduled news announcement.

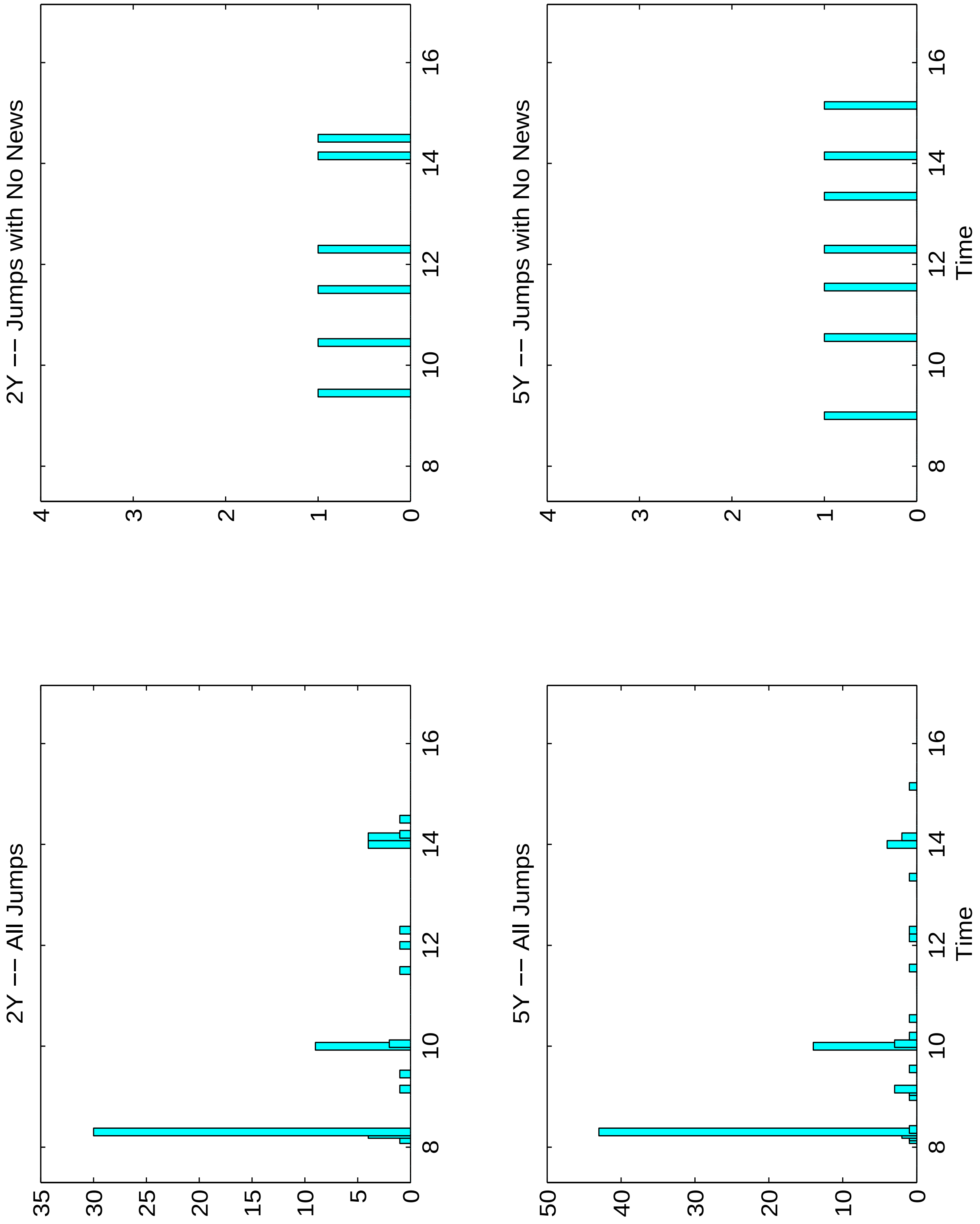


FIGURE 3

Jumps outside announcement times (10-year note)

This figure plots market activities–return and trade volume–before and after jumps outside announcement times due to different reasons.

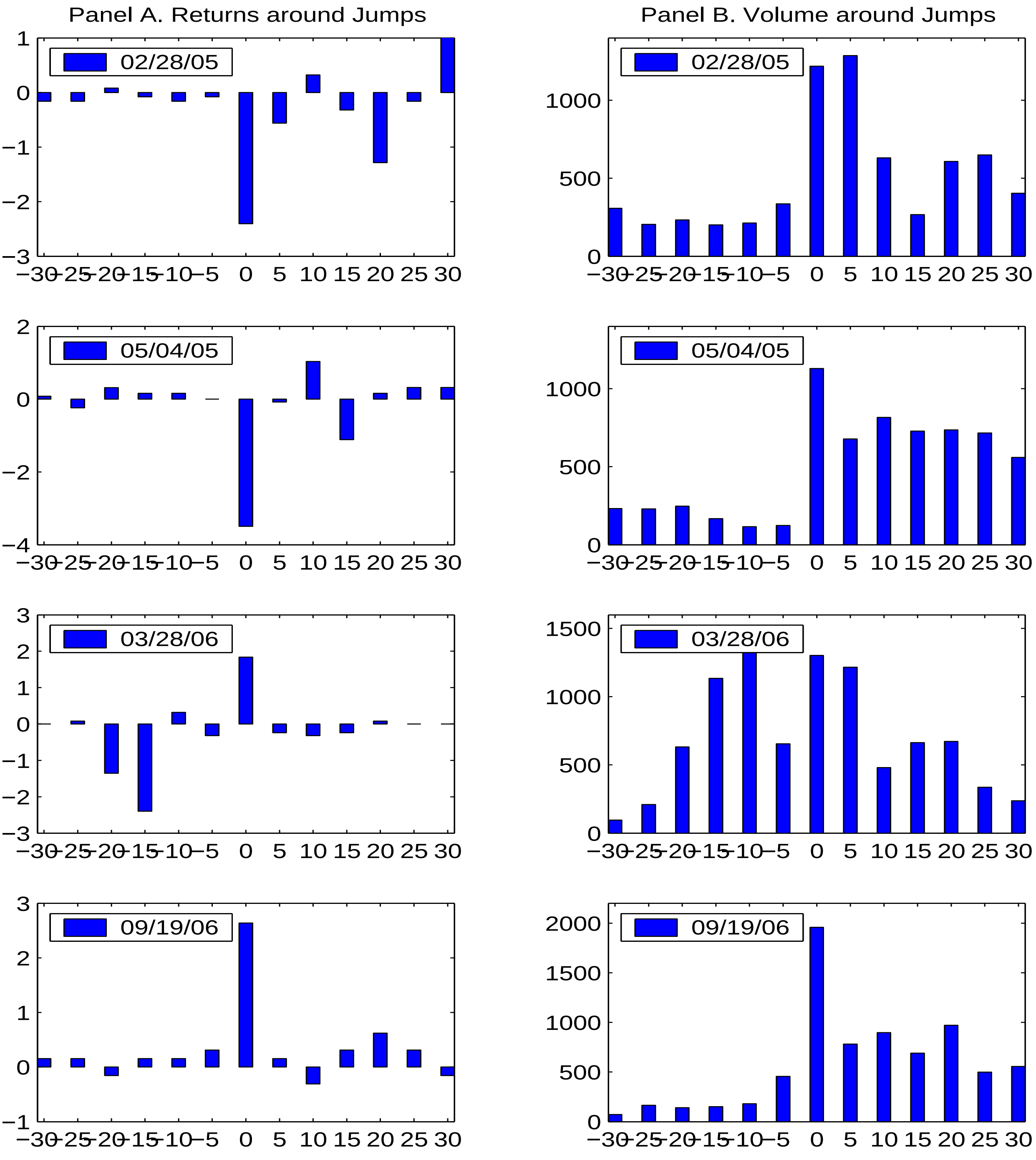
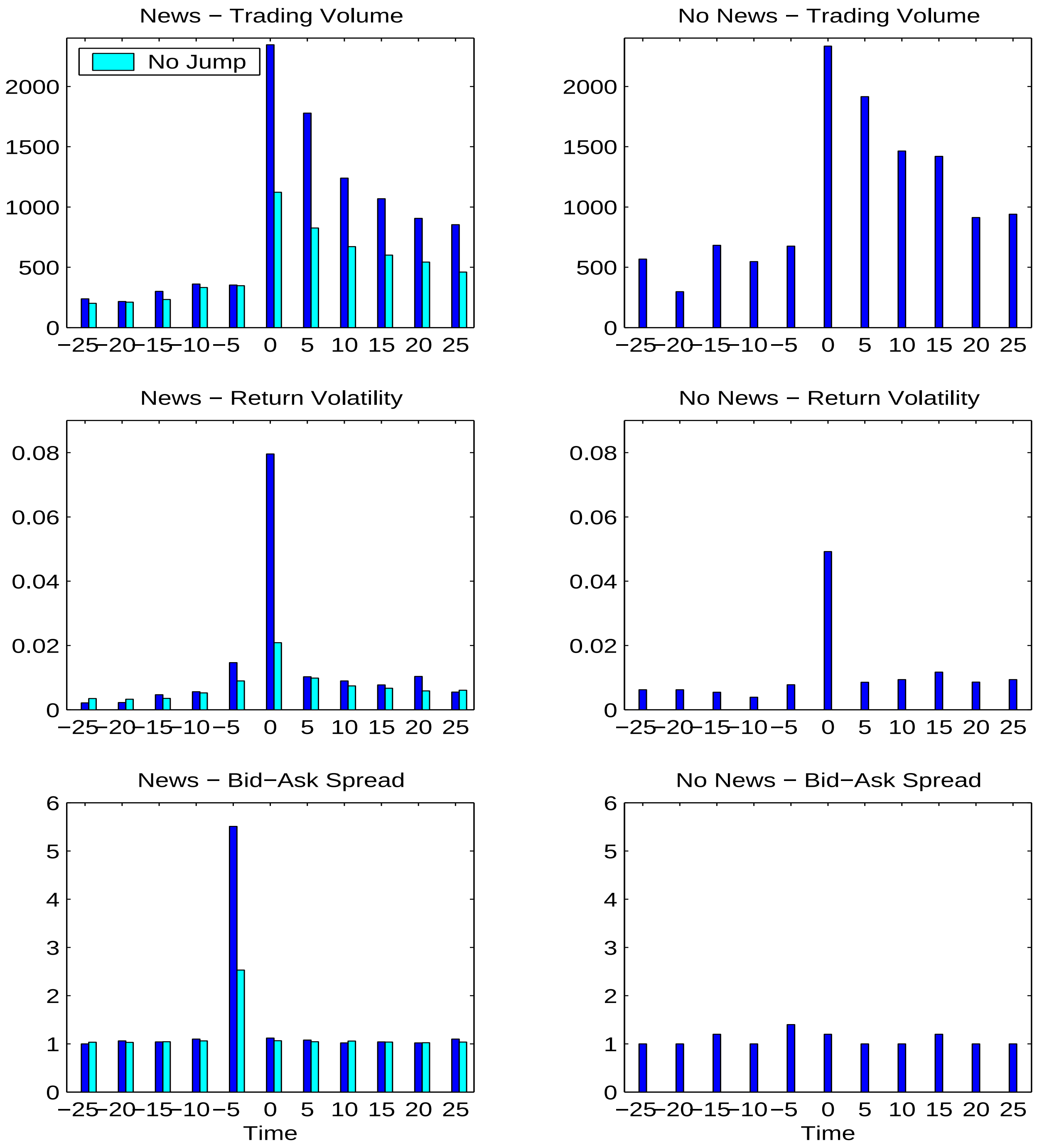


FIGURE 4

Market Activities Around Jumps (2-year note)

This figure plots market activities before and after jumps. The left column contrasts market activities around jumps occurring at announcement time to the normal announcement, i.e. there is news announcement but no jumps. The right column plots market activities around jumps outside pre-scheduled news announcement. Variables include trading volume ($ millions), return volatility (%), relative bid-ask spread ($\times 10,000$), depth of the entire order book ($ millions), depth at the best bid/ask ($ millions), total hidden depth ($ millions), and hidden depth at the best bid/ask ($ millions).


News − Trading Volume

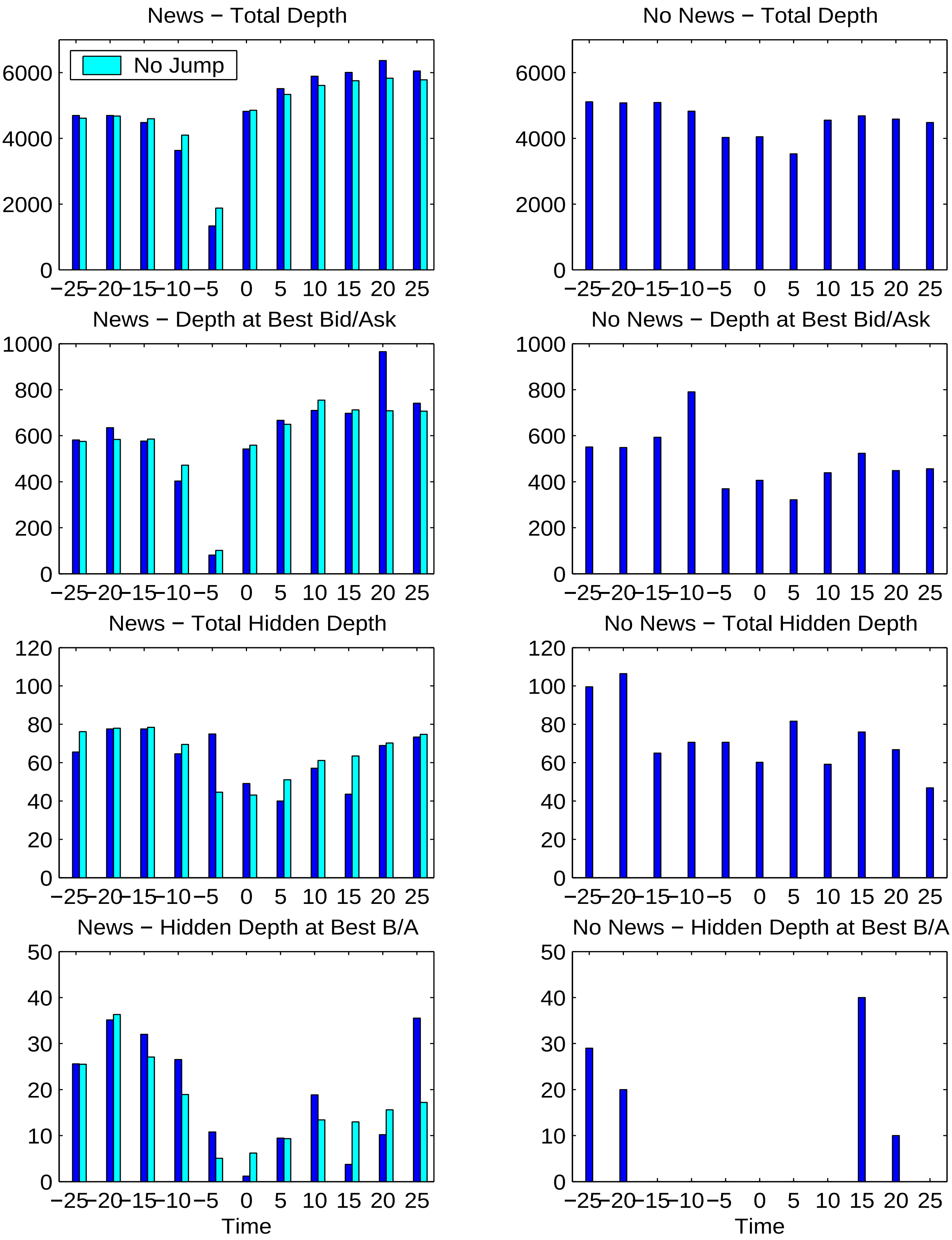
No News − Trading Volume

News − Return Volatility

No News − Return Volatility

News − Bid−Ask Spread

No News − Bid−Ask Spread


News − Total Depth
No Jump
0
2000
4000
6000
No News − Total Depth
News − Depth at Best Bid/Ask
0
200
400
600
800
1000
No News − Depth at Best Bid/Ask
News − Total Hidden Depth
0
20
40
60
80
100
120
No News − Total Hidden Depth
News − Hidden Depth at Best B/A
0
10
20
30
40
50
No News − Hidden Depth at Best B/A
−25 −20 −15 −10 −5 0 5 10 15 20 25
Time
Time