IMPLIED VOLATILITY ASYMMETRIES IN TREASURY BOND FUTURES OPTIONS

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INTRODUCTION

This article examines implied volatility asymmetries in Treasury bond futures options by modeling the times series of implied volatility. Knowledge of whether implied volatility responds differently to negative versus positive Treasury bond futures price changes is important to option market participants because rising implied volatility enhances the returns from buying options and diminishes the return from selling options.[1] The presence of implied volatility asymmetries also would represent an additional source of risk to dealers' delta hedging option positions with offsetting futures positions.

This study also has implications for the general understanding of conditional volatility asymmetries, which have been studied primarily in the equity market. These studies, including Black (1976a), Christie (1982), and Schwert (1989, 1990), demonstrate that equity market volatility is more sensitive to negative than positive equity price changes. Fleming, Ostdiek, and Whaley (1995) demonstrate the same phenomenon with the OEX volatility index (VIX). Conditional volatility asymmetries in the equity market are often referred to as the leverage effect,

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[1]Formally, the vega of an option is the derivative of its price with respect to implied volatility changes and is always positive.

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because a decrease in the stock price of a firm, holding constant both the debt level and the volatility of the return on the assets, increases financial leverage, and consequently increases the volatility of the return on equity. However, French, Schwert, and Stambaugh (1987), and Schwert (1989) demonstrate that changing financial leverage of the firm falls well short of accounting for the magnitude of the phenomenon. The same finding in the Treasury bond market, where the leverage effect is not present, would indicate that conditional volatility asymmetries exist more broadly and result from more general factors than financial leverage.

To examine implied volatility asymmetries, the times series of the implied volatility of at-the-money Treasury bond futures call options is constructed with the use of daily data from October 1982 through March 1993. The time series of implied volatility is modeled and the possibility is examined of whether implied volatility increases more following a given magnitude negative versus positive bond futures price change. Finally, this study explores the possibilities that implied volatility asymmetries are caused by a tendency for trading activity to increase more following bond futures price declines than increases and that implied volatility asymmetries are caused by extreme bond futures price changes.

The results indicate that implied volatility is more responsive to negative than positive Treasury bond futures price changes. More strikingly, no evidence suggests that implied volatility rises with the magnitude of bond futures price increases. This pronounced asymmetry is unrelated to trading volume and is not an artifact of extreme bond futures price changes.

The article proceeds as follows: The first section discusses both the methodology used to estimate implied volatility and the implied volatility estimates, the second section models the time series of implied volatility and examines possible explanations for pronounced implied volatility asymmetries, and the final section discusses the implications for trading and hedging Treasury bond futures options.

IMPLIED VOLATILITY ESTIMATION

Implied volatility is estimated from near-term, at-the-money Treasury bond futures call options from October 1982 through March 1993 by solving Black's (1976b) commodity option pricing model for the expected standard deviation of the log of Treasury bond futures price changes. Because Treasury bond futures options are American, Black's model with the Barone-Adesi and Whaley (1987) analytical approximation for American options is estimated. Black's model for call options is

$$c = e^{-rt}\,[FN(d_1) - KN(d_2)] \tag{1}$$

where $d_1 = [\ln(F/K) + 0.5\sigma^2 t]/\sqrt{\sigma t}$ and $d_2 = d_2 - \sqrt{\sigma t}$, c is the price of a European call option, r is the interest rate on the Treasury bill maturing closest to t days ahead when the option contract expires, F is the price of the bond futures contract underlying the options contract, K is the strike price, σ is the annualized standard deviation of the futures contract, and $N(\cdot)$ is the cumulative normal density function.

The Barone-Adesi and Whaley (1987) approximation for American options on futures contracts is

$$C = c + A(F/F^*)^{\gamma}, \qquad \text{when } F < F^* \tag{2}$$

and

$$C = F - K, \qquad \text{when } F \geq F^* \tag{3}$$

where C and c are American and European call options, respectively, and F^* is the futures price at which early exercise is optimal:

$$F^* - K = c + \{1 - e^{-rt}\,N[d_1(F^*)]\}\,F^*/gg$$

$$A = (F^*/\gamma)\,\{1 - e^{-rt}\,N[d_1(F^*)]\}$$

$$d_1(F^*) = [\ln(F^*/K) + 0.5\sigma^2 t]/0.5\sigma t$$

$$\gamma = [1 + \sqrt{(1 + 4\alpha/h(t))}]/2,$$

$$\alpha = (2r)/\sigma^2 \quad \text{and} \quad h(t) = 1 - e^{-rt}$$

Implied volatility estimates are obtained by substituting Eq. (1) into Eqs. (2) and (3), and then solving numerically for both implied volatility and for the futures price at which early exercise is optimal.[2]

Treasury bond futures and Treasury bond futures options were traded at the Chicago Board of Trade for the delivery months of March, June, September, and December during the sample period from October 1982 through March 1983. Treasury bond futures trading ceases on the eighth to last business day of delivery months, whereas Treasury bond futures options trading terminates on the Friday preceding the first business day of the contract month by at least 5 business days. Implied vol-

[2]The at-the-money call options used to calculate implied volatility are optimal to exercise early when they are about 20% in the money. The average difference between implied volatility estimates from Black's (1976a and 1976b) model with and without the approximation for early exercise averages $\frac{4}{100}$% and ranges from $\frac{2}{100}$ to $\frac{2}{10}$%.

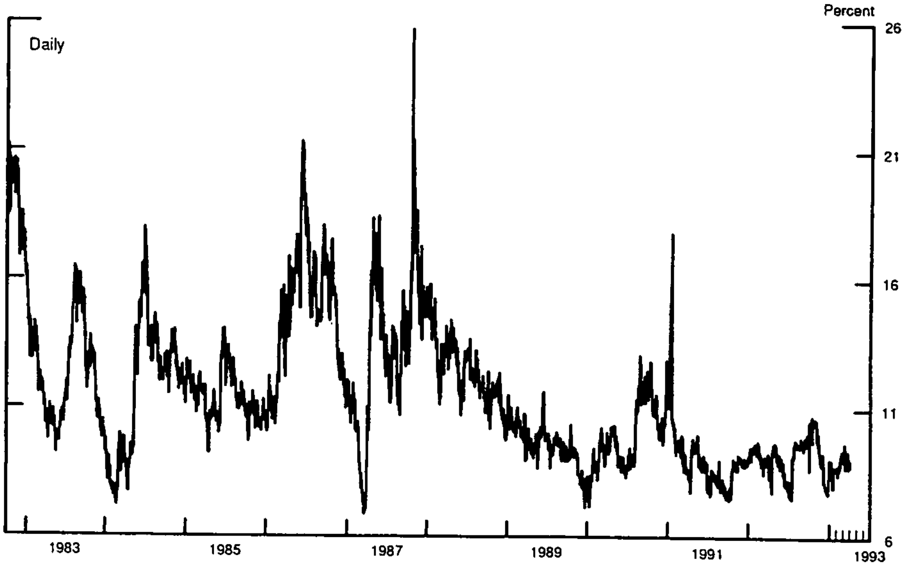

FIGURE 1
Implied volatility from near-term, at-the-money treasury bond futures call options (10/82–3/93)

atilities are calculated from call options that have 1–4 months to expiration and have strike prices closest to underlying bond futures prices.[3]

Implied volatilities for near-term, at-the-money call options are estimated for each day of the sample period. The results are shown in Figure 1. Implied volatility is generally higher and more variable during the first half of the sample period. Implied volatility peaks occur in early 1983, following the sharp drop in interest rates during the oil price declines in 1986, during the sharp bond yield increases in the spring of 1987, and leading up to the stock market crash in the fall of 1987. During the second part of the sample period, small spikes in volatility occur following the invasion of Kuwait and leading up to the Gulf War in early 1991. Because the time series of implied volatility appears to have changed at the end of 1987, the analysis of this article is conducted on the whole sample period, as well as on subperiods split at the end of 1987.

The application of Black's model to bond futures options is subject to the criticism that expected future cash flows are discounted by a fixed, risk-free interest rate, whereas bond futures prices are assumed to be stochastic. Despite this inconsistency, Black's model is widely used by

[3]The results of this article are not changed qualitatively when an average of implied volatility estimates from at-the-money calls and puts, or at-the-money puts are used. This is because of put–call parity, which causes the implied volatility of calls and puts at the same strike price to move together.

financial market participants to price Treasury bond future options. More importantly, the results of this article are not changed qualitatively when implied volatilities from 1987 through early 1993 obtained from a government securities dealer's proprietary term structure model are used.

DETERMINANTS OF IMPLIED VOLATILITY

In this section, the daily time series of implied volatility is modeled. The first model specification is

$$\begin{aligned} \mathrm{IV}_t = \beta_0 + \beta_1\, \mathrm{IV}_{t-1} + \beta_2\, [\Delta \log(P_t)^{\{+\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] \\ + \beta_3\, [\Delta \log(P_t)^{\{-\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] + u_t \end{aligned} \tag{4}$$

where IV_t is the estimated implied volatility at the close of trading on day t, $\Delta \log(P_t)$ is the first difference of the log of bond futures prices from the close of trading on day $t - 1$ to day t, $\{+\}$ and $\{-\}$ denote positive and negative bond futures price changes, and u_t is an error term. The logs of positive and negative bond futures price changes are scaled by lagged implied volatility at the close of trading on day t-1, expressed on a daily basis by dividing by the square root of 252 (the number of trading days in a year).

The model is specified similarly to an asymmetric GARCH model [see Nelson (1991) and Glosten, Jagannathan, and Runkle (1993)] and specifies that implied volatility at the close of day t is driven by its lagged value, and by separate variables for positive and negative scaled bond futures price changes from the close on day t-1 to the close on day t.[4] The reason for scaling bond futures price changes is that market participants should revise their forecasts of volatility more, and, consequently, implied volatility changes should be greater when the magnitude of bond futures price changes diverges from that predicted by implied volatility.[5] For example, larger-than-expected bond futures price changes should result in greater implied volatility increases when smaller absolute price changes, reflected by low implied volatility, are expected. Separate variables for positive and negative bond futures price changes are included to determine whether implied volatility responds differently to positive

[4]For expositional ease, scaled bond futures price changes subsequently are referred to as bond futures price changes. The positive (negative) bond futures price change variable can be thought of as the actual price change times a dummy variable that takes on the value of 1 if the price change is positive (negative) and zero otherwise.

[5]If the log of daily bond futures price changes is normally distributed with a mean equal to zero and a standard deviation equal to estimated implied volatility expressed on a daily basis, then $\Delta \log(p_t)/(\mathrm{IV}_{t-1}/\sqrt{252}) \sim N(0,1)$.

TABLE I

The Determinants of Daily Implied Volatility from Call Options on Treasury Bond Futures Contracts (October, 1982–March, 1993) $IV_t = \beta_0 + \beta_t\, IV_{t-1} + \beta_2\, [\Delta \log(P_t)^{\{+\}}/(IV_{t-1}/\sqrt{252})] + \beta_3\, [\Delta \log(P_t)^{\{-\}}/(IV_{t-1}/\sqrt{252})] + u_t$

	10/1982–3/1993	*10/1982–12/1987*	*1/1988–3/1993*
β_0	−0.0000	−0.0000	−0.0001
	(0.001)	(0.0001)	(0.0001)
β_1	0.974**	0.972**	0.958**
	(0.006)	(0.009)	(0.013)
β_2	−0.0000	0.0009	−0.0011**
	(0.0000)	(0.0007)	(0.0004)
β_3	−0.0023**	−0.0035**	−0.0019**
	(0.0003)	(0.0006)	(0.0002)
R^2	0.95	0.96	0.92

Note: IV is estimated implied volatility from near-term, at-the-money call option prices at the close of trading, *P* is the closing bond futures price, and {+} and {−} denote positive and negative scaled bond futures price changes. The model is estimated by OLS with White's (1980) correction for heteroskedasticity and with Hansen's (1982) correction for autocorrelation through 12 lags.

**Significant at the 1% level.

and negative bond futures price changes. If both greater scaled bond futures price increases and decreases give rise to higher implied volatility, β_2 should be significantly positive and β_3 should be significantly negative. If implied volatility increases more in response to negative than positive bond futures price changes, $|\beta_3| > |\beta_2|$.

Equation (4) is estimated with daily data over the sample period from October 1982 through March 1993, and for subperiods from October 1982 through December 1987, and from January 1988 through March 1993 by OLS with Hansen's (1982) correction for autocorrelation through 12 lags and White's (1980) correction for heteroskedasticity. All variables in the model are detrended with the use of the residuals from regressions of each variable on a constant and a linear time trend because of clear trends in implied volatility and in some of the other variables in the models estimated later in this section.

The results for the entire sample period in the first column of Table I indicate that implied volatility follows a mean-reverting process, as the coefficient on lagged implied volatility is significantly less than 1 at the 5% confidence level using a Dickey–Fuller *t* test. The coefficient on lagged implied volatility for the entire sample period indicates that implied volatility shocks have half-lifes of about 26 days. The results for the entire sample period and for both subperiods indicate that greater bond futures price declines lead to higher implied volatility at the 1% confidence level. For the entire sample period, a 1% greater bond futures price decline is associated with a $\frac{2}{10}$% implied volatility increase. By contrast, greater bond futures price increases do not lead to significantly higher implied volatility in the whole sample period and in the first subperiod. In the second subperiod, greater bond futures price increases lead to significantly lower rather than higher implied volatility. Thus, not only is implied volatility more responsive to negative than positive bond futures price changes; there is no evidence that larger bond futures price increases lead to higher implied volatility and there is some evidence to the contrary.

A reason for implied volatility to respond more to negative than to positive bond futures price changes may be a tendency for more active trading—and consequently greater volatility—to be associated with greater negative than greater positive bond futures price changes. According to this hypothesis, trading volume rather than the direction of bond futures price changes affects implied volatility. If trading volume is left out of the model, the direction of bond futures price changes may spuriously enter the model as a proxy for an omitted trading volume variable. In the equity market, Gallant, Rossi, and Tauchen (1992) find that trading volume plays a significant role in explaining conditional volatility asymmetries. When those authors condition stock price changes on trading volume, conditional volatility asymmetries are less pronounced. A similar link may exist in the bond futures market because (1) unreported Granger causality tests in the present article indicate that greater bond futures price increases lead to significantly lower trading volume, whereas larger bond futures price declines lead to significantly higher trading volume, and (2) Bessembinder and Sequin (1993) find that increased trading volume in the bond futures market is associated with higher price volatility, ceteris paribus.

Whether the finding of pronounced conditional volatility asymmetries is explained by trading volume differences is next examined. The model that is estimated to test this hypothesis is

$$\begin{aligned} \mathrm{IV}_t = {} & \beta_0 + \beta_1 \, \mathrm{IV}_{t-1} + [\beta_2 + \beta_5^* \log(\mathrm{TVOL}_t)]^* \\ & [\Delta \log(P_t)^{(+)} (\mathrm{IV}_{t-1}/\sqrt{252})] + [\beta_4 + \beta_5^* \log(\mathrm{TVOL}_t)]^* \\ & [\Delta \log(P_t)^{(-)} / (\mathrm{IV}_{t-1}/\sqrt{252})] \end{aligned} \tag{5}$$

where TVOL is the daily trading volume for all outstanding Treasury bond futures contracts. The model decomposes the coefficient on positive and negative bond futures price changes into a constant and a component

TABLE II

The Determinants of Daily Implied Volatility from Options on Bond Futures Contracts Allowing for Trading Volume Effects $\mathrm{IV}_t = \beta_0 + \beta_1 \mathrm{IV}_{t-1} + [\beta_2 + \beta_3^* \log(\mathrm{TVOL}_t)]^* [\Delta \log(P_t)^{\{+\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] + [\beta_4 + \beta_3^* \log(\mathrm{TVOL}_t)]^* [\Delta \log(P_t)^{\{-\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] + u_t$

	10/1982–3/1993	*10/1982–12/1987*	*1/1988–3/1993*
β_0	−0.0000	−0.0001	−0.0001
	(0.0000)	(0.0001)	(0.0001)
β_1	0.973**	0.972**	0.957**
	(0.006)	(0.009)	(0.013)
β_2	−0.0000	0.0009	−0.0009*
	(0.0005)	(0.0007)	(0.0003)
β_3	−0.0131	0.0028	−0.0209
	(0.0131)	(0.0154)	(0.0164)
β_4	−0.0026**	−0.0034**	−0.0018**
	(0.0003)	(0.0005)	(0.0002)
β_5	−0.0073	−0.0091	−0.0039
	(0.0082)	(0.0138)	(0.0061)
R^2	0.95	0.94	0.92

Note: IV is estimated implied volatility from near-term, at-the-money call option prices at the close, *P* is the closing bond futures price, {+} and {−} denote positive and negative scaled bond futures price changes, and TVOL is trading volume on all outstanding Treasury bond futures contracts. The model is estimated by OLS with White's (1980) correction for heteroskedasticity and with Hansen's (1982) correction for autocorrelation through 12 lags.
*Significant at the 5% level.
**Significant at the 1% level.

that is a linear function of the log of the (detrended) trading volume. If the asymmetric reaction of implied volatility to positive and negative bond futures price changes is mitigated by controlling for the interaction between bond futures price changes and trading volume, both larger magnitude bond futures price increases and decreases should be associated with higher implied volatility, and therefore β_2 and β_4 should be significantly positive and negative, respectively, and of the same magnitude. If the relationship between the magnitude of bond futures price changes and implied volatility is a linear positive function of trading volume, β_3 should be significantly positive, whereas β_5 should be significantly negative. In this case, greater positive and negative bond futures price changes that are associated with increased trading volume should be associated with higher implied volatility.

The estimation results in Table II indicate that the relationship between bond futures price changes and implied volatility is not significantly affected by trading volume, as both β_3 and β_5 are not statistically significant. The inclusion of trading volume does not qualitatively change the previous results. Larger bond futures price increases are not associated with significantly higher implied volatility in the whole sample period and in the first subperiod, and again are associated with significantly lower implied volatility in the second subperiod. Greater magnitude bond futures price decreases are associated with significantly higher implied volatility in the whole sample period and in each subperiod. In addition, the basic results are unchanged when the log of trading volume is included in the model as a separate regressor (not shown).

Another possibility is that the pronounced asymmetry of implied volatility with respect to positive and negative bond futures price changes may be caused by extreme bond futures price changes. This possibility is investigated by reestimating the model in eq. (4) with separate variables for positive and negative bond futures price changes that are more than two standard errors from the mean absolute bond futures price change. The model that is estimated is

$$\begin{aligned} \mathrm{IV}_t = \beta_0 &+ \beta_1\,\mathrm{IV}_{t-1} + \beta_2\,[\Delta \log(P_t)^{\{+\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] \\ &+ \beta_3\,[\Delta \log(P_t)^{\{+\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] * \mathrm{TAIL}_t \\ &+ \beta_4\,[\Delta \log(P_t)^{\{-\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] \\ &+ \beta_5\,[\Delta \log(P_t)^{\{-\}}/(\mathrm{IV}_{t-1}/\sqrt{252})] * \mathrm{TAIL}_t + u_t \qquad (6) \end{aligned}$$

where TAIL is a dummy variable that takes on the value 1 when the absolute magnitude of bond futures price changes is more than 2 standard errors away from the mean, and 0 otherwise. If positive and negative bond futures price changes in the tails of the distribution have an incrementally greater effect (per unit of price change) on implied volatility than those that are not, β_3 will be significantly positive and β_5 will be significantly negative. If the asymmetry of implied volatility with respect to positive and negative bond futures price changes is caused by the tails of the bond futures price change distributions, positive and negative bond futures price changes outside the tails of the distribution should have the same effect on implied volatility, and hence β_2 should be significantly positive, β_4 should be significantly negative, and these coefficients should be of the same magnitude.

The results in Table III indicate that implied volatility asymmetries are not caused by extreme bond futures price changes. The coefficient on bond futures price increases in the central part of the distribution is significantly negative, indicating that larger bond futures price increases are associated with lower implied volatility, whereas the coefficient on bond futures price decreases in the central part of the distribution is

TABLE III

The Determinants of Daily Implied Volatility from Call Options on Bond Futures Allowing for Different Effects of Large Board Futures Price Changes

$$IV_t = \beta_0 + \beta_1 IV_{t-1} + \beta_2 [\Delta \log(P_t)^{\{+\}}/(IV_{t-1}/\sqrt{252})] + \beta_3 [\Delta \log(P_t)^{\{+\}}/(IV_{t-1}/\sqrt{252})]^* TAIL_t + \beta_4 [\Delta \log(P_t)^{\{-\}}/(IV_{t-1}/\sqrt{252})] + \beta_5 [\Delta \log(P_t)^{\{-\}}/(IV_{t-1}/\sqrt{252})]^* TAIL_t + u_t$$

	10/1982–3/1993	*10/1982–12/1987*	*1/1988–3/1993*
β_0	−0.0003**	−0.0001	−0.0001
	(0.0001)	(0.0002)	(0.0001)
β_1	0.974**	0.973**	0.959**
	(0.006)	(0.009)	(0.012)
β_2	−0.0009**	−0.0011*	−0.0007*
	(0.0003)	(0.0005)	(0.0003)
β_3	0.0014	0.0032**	−0.0007
	(0.0008)	(0.0013)	(0.0006)
β_4	−0.0020**	−0.0021**	−0.0018**
	(0.0004)	(0.0006)	(0.0004)
β_5	−0.0010	−0.0021	−0.0001
	(0.0006)	(0.0011)	(0.0001)
R^2	0.95	0.95	0.92

Note: IV is estimated implied volatility from near-term, at-the-money call option prices at the close, P is the closing bond futures price, TAIL is a dummy variable that takes on the value 1 when the absolute scaled bond futures price changes is more than 2 standard errors from the mean and 0 otherwise. The model is estimated by OLS with White's (1980) correction for heteroskedasticity and with Hansen's (1982) correction for autocorrelation through 12 lags. Standard errors are shown in parentheses.
*Significant at the 5% level.
**Significant at the 1% level.

significantly negative, indicating that larger bond futures price decreases are associated with higher implied volatility. Thus, for changes within the central part of the distribution, implied volatility is a decreasing function of bond futures price changes. The coefficient on bond futures price increases in the tail of the distribution is significantly positive only in the first subperiod—indicating an incremental positive effect on implied volatility—but not in the second subperiod or in the whole sample. However, even in the first subperiod the overall effect of a bond futures price increase outlier ($\beta_2 + \beta_3$) is not significantly positive. Also, the results indicate the absence of an incremental effect on implied volatility from bond futures price declines in the tail of the distribution. These overall findings are robust to defining the tails of the distribution to include bond futures price changes greater than 2 ½ or 3 standard errors from the mean.[6] Thus, outliers do not drive the results.

[6]The scaled bond futures price change distribution is somewhat skewed to the left with a statistically

Another potential explanation for this article's findings may be that when bond futures prices fall, call options from which implied volatility is estimated are either further out of the money or less in the money, which results in higher implied volatility. However, this possibility should be mitigated by the fact that call options from which implied volatilities are calculated are the options closest to the money. Also, unreported results indicate that the results of this article are robust to including a variable for the moneyness of the options used to calculate implied volatility.

Another possibility is that the increased prevalence of covered call writing strategies is responsible for implied volatility asymmetries. However, such trading strategies would appear to work against the findings of this article. Suppose that call options are sold on a delta-hedged basis against long futures positions. If bond futures rise sharply, a rebalanced delta-hedged position requires fewer written call options, leading to purchases of calls, which would tend to increase implied volatility. If bond futures prices fall sharply, a rebalanced delta-hedged position requires more written calls, which leads to sales of calls, which would decrease implied volatility.

CONCLUSIONS

This article demonstrates that implied volatility estimated from call options on Treasury bond futures contracts is highly asymmetric with respect to bond futures price changes, rising with negative but not positive bond futures price changes. The implied volatility asymmetry is robust to conditioning on trading volume and is not driven by extreme bond futures price changes. The finding of implied volatility asymmetries is consistent with Brunner and Simon (1996), who find that the conditional volatility of excess returns at the long end of the Treasury bond spot market increases more following equal-magnitude positive relative to negative excess return innovations. A potential macroeconomic explanation for this phenomenon may be a strong tendency, documented by Brunner and Hess (1993), for inflation volatility to rise as the level of inflation increases. According to this view, when data releases cause financial markets to revise inflation expectations upward, bond futures prices typically

significant skewness coefficient of -0.21. Using a given standard error cutoff to classify scaled bond futures price changes as in the tails could be misleading because of skewness if more negative price changes than positive price changes are classified as in the tails. However, the $2\frac{1}{2}$ standard error cutoff used in this article results in 32 positive and 26 negative scaled bond futures price changes as in the tails. Also, the results are robust to defining the tails as the largest 1% bond futures price increases and decreases.

fall sharply and the greater volatility of inflation at higher levels of inflation causes increased volatility of bond futures prices, which leads to higher implied volatility.

The findings of this article provide an additional incentive for traders anticipating significant bond futures price declines to buy puts rather than to sell futures, because if expectations are realized, implied volatility increases will enhance returns on puts. The absence of a tendency for implied volatility to increase with the magnitude of positive bond futures price changes, and some evidence to the contrary, makes buying call options less attractive for traders expecting large bond futures price increases.

Implied volatility asymmetries also increase the riskiness of delta-hedging option positions. For example, dealers who sell options typically hedge by establishing an offsetting position in bond futures in proportion to the delta or the sensitivity of the price of the option with respect to bond futures price changes. These dealers have short volatility and must rebalance their positions as bond futures prices change. Dealers would lose from a large jump in bond futures prices in either direction because they are short volatility, but a large bond futures price decline would cause dealers to lose more, to the extent that implied volatility increases, and the option that dealers are short becomes more expensive.

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