Interest Rate Conundrum*

Roger Craine
University of California, Berkeley

Vance L. Martin
University of Melbourne

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Abstract

In June of 2004 the Fed began relentlessly tightening policy. They raised the Federal Funds Target (Target) from 1% to 5 1/4% in 1/4% increments at seventeen consecutive meetings. While short rates dutifully followed the Target up, long maturity rates actually fell. Alan Greenspan in 2005 Congressional testimony labeled the strange behavior of the spread between long rates and the Target a "conundrum". This paper examines the conundrum. We present robust empirical evidence that the increase in foreign holdings of US Treasury bonds explains at least half of the decline in long maturity rates. Foreign holdings of US Treasury debt with a maturity over one year grew from 20% in 1994 to 57% in 2007.

KEYWORDS: Forward Rates, Money and Macroeconomic surprises, Foreign Demand for US Treasury Bonds

JEL Classification: E44, E52, G12, G14

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1 Introduction

On June 30, 2004 the US Federal Reserve began a relentless tightening process after three years of loose monetary policy. The Fed increased the Federal Funds Target rate (Target) by 1/4% at seventeen consecutive Federal Open Market Committee (FOMC) meetings. The Target rose from a historic low of 1% to 5 1/4% . Economic policy makers and pundits worried that tighter monetary policy might raise long maturity yields strangling the nascent economic recovery. Instead the ten year forward rate actually fell from 6.5% in July of 2004 to 5.2% by February of 2005. Alan Greenspan, Chairman of the Federal Reserve Board at the time, famously labeled the strange behavior of the spread between the Target and long rates "a conundrum" in February 2005 Congressional testimony.[1]

Figure 1 shows the *Target*, the ten year forward rate (*Forward10*) and the one year yield (*Yield01*) from 1990 through 2007. No wonder Greenspan was puzzled by the behavior of long maturity interest rates in 2005. In 1990 the Fed lowered the Target rate by 5% and in 1993 they increased the Target by 3% The ten year forward rate followed the Target down and up. Then in 1999 when the Fed increased the Target rate the ten year forward rate dutifully followed the Target up. The interval from 2004 to 2006 is an anomaly. The Fed rapidly lowered the Target from 6.5% to 1%. The ten year forward rate only fell by 30 basis points. And when the Fed began raising the Target in June of 2004 long rates stubbornly refused to go up. In fact the ten year forward rate fell until by August 2006 it was less than the Target rate.

Greenspan[2] believed that the market underestimated the riskiness of long maturity bonds. Kim and Wright (2006) estimated a three factor affine model of the yield curve and found that the risk premium on ten year bonds fell by 0.8% from 2004 to 2005. Cochrane and Piazzesi (2006) also estimated a factor model of the yield curve and they also found that the spread between long and short maturity yields fell. The beauty of a factor model is that the unobservable statistical factors, molded by the hands of a skilled econometrician, capture the essential features of the data. The curse of a factor model is that the factors are unobservable statistical constructs. The economic forces driving the yields remain hidden. Kim and Wright list five possible economic sources and say "the term premium estimates that we report in this paper should be thought of as "catch-all" measures that combine all of these effects and indeed anything else that might affect the price of Treasury securities other than expected future monetary policy." Cochrane and Piazzesi reason that only factors that

[1] For Greenspan's and other Fed officials testimony and speeches see,

https://www.federalreserve.gov/newsevents/default.htm

[2] Same Congressional testimony February 2005.

Figure 1: Federal funds target rate (Target), one year yield (Yield01) and ten year forward rate (Forward10): percentages, daily data from 1990 to 2006.

have a "level" effect on the term structure can explain long maturity risk premia. For them this rules out monetary surprises which have a "slope" effect, but that only eliminates one variable from the long list of economic variables that might explain the conundrum.

Ben Bernanke, Greenspan's successor as Chairman in 2006, in a frequently quoted March 2005 speech suggested that an international savings glut drove long term yields down. Warnock and Warnock (2006) using an augmented IS-LM model found that increased foreign demand in 2004-2005 kept the ten year Treasury yield 0.9% below what it would have been otherwise. And Bernanke, Reinhart, and Sack (2006) found evidence that Japanese intervention in currency markets lowered US yields. Bernanke in a later speech (March 2006) that focused on the yield curve said, "A reasonable conclusion is that the accumulation of dollar reserves abroad has influenced U.S. yields, but reserve accumulation abroad is not the only, or even the dominant, explanation for their recent behavior." He noted, however, that the empirical evidence was scarce.

We provide robust empirical evidence that large increases in foreign purchases drove bond prices up (forward rates and yields down) and that the effect is large and long lived. The accumulation of foreign holdings of US Treasury Debt explains at least half the decline in the ten year forward rate in 2005-2006. Section 3 presents the results for a mean reverting specification for forward rates and Appendix B gives the results for a vector error correction

specification in which the forward rates are cointegrated.

In theoretical asset pricing models, e.g., the CAPM or CCAPM, changes in tastes, technology, or the distribution of wealth change the demand for assets and expected returns. The persistent US trade deficits meant foreigners accumulated a larger share of US portfolio assets. They invested heavily in Treasury securities and they invested more as the US trade deficit and their wealth grew. In 1994 foreigners owned 19% of the long term (maturity over one-year) US marketable Treasury debt and 5% of US equity. By 2007 foreigners owned 57% of long term US Treasuries, and they owned 11% of US equities[3] One would expect such a large change in demand for Treasury debt to affect prices and it did.

We estimate two models with daily data in which forward rates are driven by exogenous monetary and macroeconomic surprises and the foreign demand for US Treasuries and the supply of US Treasuries. Section 4 reports the results for a mean-reverting specification for forward rates. Appendix B reports the results for an error correction specification in which the ten and five year forward rates are cointegrated nonstationary processes. The results are remarkably similar. We find that the ten year forward rate was at least 0.5% lower in 2005 than it would have been if foreign holdings of Treasury debt would have remained at the level they were at the beginning of 2004. We don't find much of a supply effect. In theory a decrease in supply should help explain the conundrum, but the empirical evidence is not robust. The other exogenous factors – monetary policy and macroeconomic surprises significantly affect forward rates, but the effects are small and not persistent. Monetary and macroeconomic surprises do not explain the conundrum.

The paper is organized as follows. Section 2 presents an empirical model of yields. Section 3 presents the data. Section 4 gives the empirical results and analysis and Section 5 concludes. Appendix A has detailed results for the mean-reverting specification and Appendix B has detailed results for the error correction specification.

2 An Empirical Model of Forward Rates

Our empirical model modifies popular macroeconomic models that explain daily changes in forward rates or yields, with exogenous surprises to analyze the conundrum. Kuttner (2001) initiated these models when he showed that yield changes responded to monetary policy surprises, i.e. surprises in the Target rate, m.[4] Gurkaynak, Sack, and Swanson (2005) (GSS) added a vector of macroeconomic surprises, x, to the money surprise models and estimated a model of changes in the forward rates.

[3] See http://www.treas.gov/tic/shl2007r.pdf. Foreigners also seemed to prefer longer maturity Treasurys. In 2002 – the first year the Treasury survey showed short maturity Treasurys (under one-year) – the ratio of short to long maturity Treasury debt held by foreigners was 24%. By 2007 the ratio fell to 12%.

[4] The Data section fully describes all the variables and the sources.

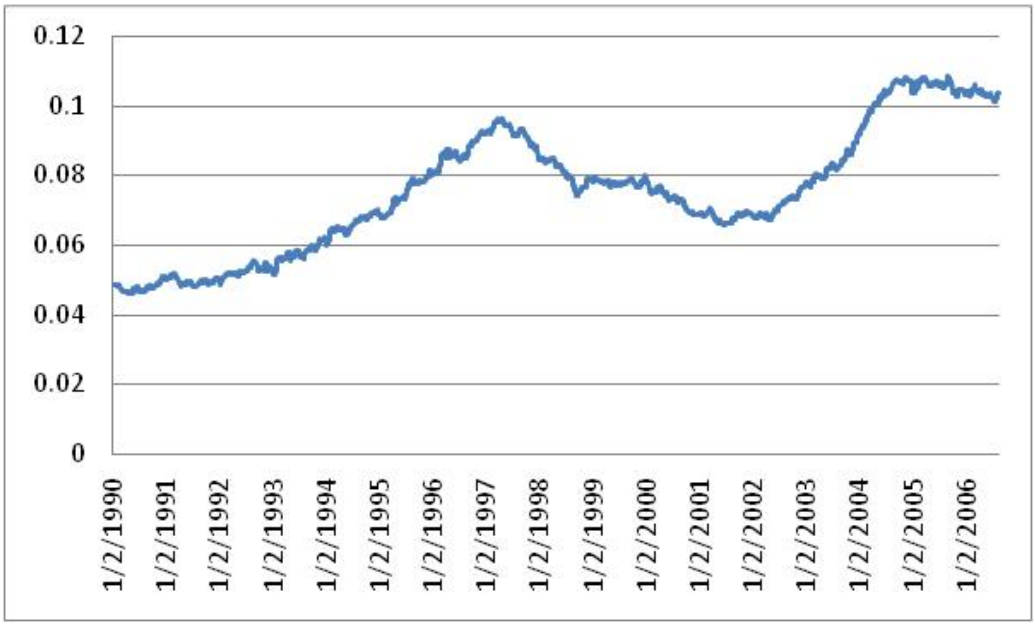

Figure 2: Foreign Official Holdings of US Treasury Debt scaled by US Personal Income: daily data from 1990 to 2006.

We make two changes in the GSS specification to analyze the conundrum. First and most important, we add a proxy for foreign demand, *oit*, and for the outstanding supply of Treasuries by maturity, $tr(n)$ where n denotes maturity. Second we specify a mean-reverting process for the forward rate in place of GSS's random walk specification. Our model is

$$f(n)_t = a_0(n) + a(n)f(n)_{t-1} + b_1(n)oit_t + b_2(n)tr(n)_t + c(n)m_t + d(n)'x_t + e(n)_t, \quad (1)$$

where $f(n)$ is the forward rate on a bond that matures in n years, and $e(n)$ denotes an idiosyncratic error.

Conceptually the mean-reverting specification also is important. In equation (1) the proxy bond demand and supply variables, *oit* and *tr* respectively, have permanent effects on the level of forward rates as suggested by the theory, but monetary and macroeconomic surprises have no permanent effects on the level of forward rates.[5] Empirically the distinction between mean-reverting and a specification with unit roots does not seem to be

[5] The unconditional expectation of equation (1) is

$$Ef(n) = a_0(n) + a(n)Ef(n) + b_1(n)Eoit + b_2(n)Etr.(n)$$

The monetary and macroeconomic surprises have an expected value of zero and do not affect the unconditional (stationary state) mean of the forward rates. Foreign holdings of US Treasuries and the supply of US Treasuries affect the mean of forward rates.

very important. Appendix B shows that the results for a vector error correction model are essentially the same as the results for the mean-reverting specification in equation (1).

3 Notation and Data

3.1 Notation

This subsection presents the standard notation for continuously compound zero coupon bonds. The maturities n are measured in annual units and time t in daily units.

Let

$$B(n)_t \equiv e^{-y(n)_t n} 1,$$

denote the current price of a bond of maturity n that pays one, (1), at maturity, and

$$y(n)_t \equiv -\frac{1}{n} \ln B(n)_t,$$

denote the current yield to maturity. Finally define

$$f(n)_t \equiv ny(n)_t - (n-1)y(n-1)_t,$$

the current one year forward rate linking the yield on a bond with maturity $n-1$ to the yield on a bond with maturity n.

Yields express the current average interest rate over the maturity of the bond. Forward rates are the current implied one-period rates that link adjacent maturity bond yields. Using these definitions the yield on a bond of maturity n can be expressed as the average of the n forward rates

$$y(n)_t \equiv \frac{1}{n} \left(f(1)_t + f(2)_t + \cdots + f(n)_t \right).$$

The forward rates decompose the average interest rate over the life of the bond into a sequence of one-period rates for each maturity which makes it easier to correlate movements in the driving economic variables with specific maturities.

3.2 Data

We use daily data from January 1990 through August 2006.

3.2.1 Yields and Forward Rates

We get the yields and forward rates from "The U.S. Treasury Yield Curve: 1961 to the Present", Gurkaynak, Swanson, and Wright (GSW), https://www.federalreserve.gov/pubs/feds/2006/index.html.

GSW interpolate observable bond data to compute prices, yields, and forward rates daily for Government bonds with annual maturities out to thirty years. To verify that the interpolation didn't over-smooth the data, we compared the GSW yields with the yields implied by market determined daily Eurodollar swap rates for maturities out to ten years. The correlation between the GSW yields and the implied SWAP rate yields exceeded 0.99 for all maturities. The Eurodollar swap market was thin before 1996 and is thin for maturities over ten years. We used the more comprehensive GSW data.

3.2.2 Exogenous Driving Variables

Foreign Holding of US Treasury Securities The most timely and accurate source of foreign holdings of US Treasury debt is the Federal Reserve Board's (FRB) weekly H4.1 release of US Government securities held in custody at the Federal Reserve Bank of New York (FRBNY) on behalf of foreign official institutions (central banks and finance ministries), see www.federalreserve.gov/releases/h41/.[6] The official holdings represent 50 to 75% of the total foreign holdings of long term US Treasury debt over our sample, see Table 6, http://www.treas.gov/tic/shl2007r.pdf.

Figure 2 shows the Official International holding of Treasuries OIT, scaled by US Personal Income PI.[7] We normalized by the official foreign holdings by Personal Income to induce stationarity and cancel nominal units. Our proxy measure of *foreign demand* is

$$oit_t \equiv \frac{OIT_t}{PI_t}.$$

We would prefer foreign holdings by maturity, but the data do not exist. The alternative data source is the Treasury International Capital System (TCI) which reports monthly flows of long term (over one year) US securities purchased by foreigners.[8] We chose the more timely and accurate H4.1 release data.

Supply of Treasury Debt by Maturity We constructed a monthly series for the outstanding value of Treasury debt by annual maturity $TR(n)$, from the CRSP "Monthly Treasuries" data file. Each month we cumulated the outstanding face value of Treasuries

[6] The H4.1 data on the FRB website begins in 1996. We thank the FRB for providing us with data from 1990 to 1996.

[7] Personal Income gets reported monthly. Broader measures, eg GDP, are available only quarterly. We downloaded Personal Income from, http://research.stlouisfed.org/fred2/.

[8] The monthly Treasury International Capital System (TCI) report, http://www.treas.gov/tic/ presents a more comprehensive picture with respect to holdings among assets, but not with respect to debt maturity. The TIC data breaks the monthly capital flows into 34 categories that includes the foreign purchases of US Treasury debt, US Agency debt, equity, private equity, and so on. Neither the FRB H4.1 release nor the TIC report a decomposition by maturity. The FRB H4.1 reports total holdings and the TIC reports all holdings over one year in maturity. The TCI data have more detail about asset composition, but are less accurate and less timely. Warnock and Warnock (2006) use annual benchmark surveys to adjust the monthly TCI and they kindly shared their benchmark data with us. We ended up using the FRB H4.1 releases.

with maturity dates less than one year, and with maturity dates between one and two years, and so on. We scaled the supply of Treasury debt by US Personal Income

$$tr(n) = \frac{TR(n)}{PI}.$$

Monetary Policy Surprises Kuttner's seminal paper (2001) started the empirical money surprise literature. Kuttner showed that yield changes respond to monetary policy surprises, but not anticipated Target changes. Kuttner defined a money surprise as an unanticipated change in the Fed's monetary Target rate. Money surprises can occur only on monetary event days. Event days are days that the Fed changes the target rate, or days that the Fed meets to consider Target changes but makes no change. Kuttner measured the surprise as the weighted change in the Fed Funds Futures rate on event days.[9]

3.2.3 Macroeconomic Surprises

GSS added macroeconomic surprises to the money surprise model. The macroeconomic surprises are the first released (unrevised data) of major macroeconomic indicators minus the median forecast of the release collected by Action Economics on the Friday proceeding the release. Haver Analytics (http://www.haver.com/) distributes the data. We use surprises for Capacity Utilization, Consumer Confidence, Consumer Price Index, Advance GDP, Index of Business Activity (NAPM) , Nonfarm Payroll, New Home Sales, and Retail Sales.

4 Results

To explain the conundrum (i) the estimated coefficients on long maturity, eight to twelve years, on forward rates in equation (1) must be statistically significant, and (ii) the driving variables must move in such a way that their cumulative effect reduces long maturity forward rates substantially below what they would have been if the driving factor hadn't changed. This section first looks at the estimated coefficients and then analyzes the cumulative marginal impact of the driving variables on long maturity forward rates in 2005-2006.

4.1 Estimated Coefficients

We estimated equation (1) for forward rates with maturities from one to fifteen years. We used daily data from January 1990 through December 2003. The estimation period ends seven months before the conundrum period when the Fed began raising the Target rate on June 30, 2004.

[9] We thank Andrew Swiston of the IMF for supplying us with Kuttner money surprises.

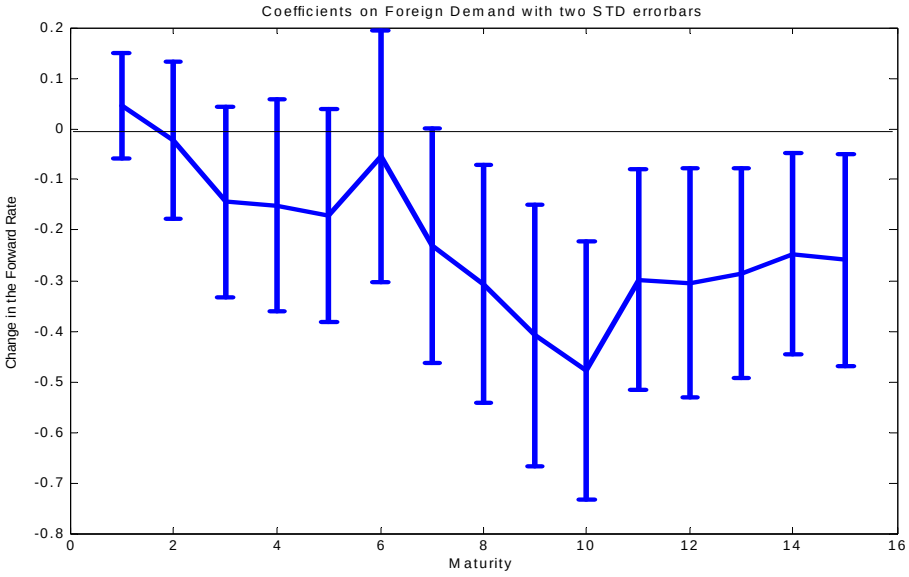

Figure 3: Change in the Forward rate (%) for maturities $n = 1$ to $n = 15$, from Foreign Demand with their two standard deviation errorbars.

4.1.1 Factors that Could Explain the Conundrum

Factors that could explain the conundrum have statistically significant coefficients on long maturity forward rates. This subsection shows graphs for selected factors. Appendix A, Tables A1 to A3, contain the parameter estimates and some summary statistics.

Foreign Demand: Figure 3 shows the estimated coefficients on foreign demand with their two standard deviation errorbars. The coefficients on Foreign Demand show exactly the pattern we are looking for. They are statistically insignificant until maturity of eight years; foreign demand does not affect short maturity forward rates. They are large and statistically significant for maturities eight through fifteen years. An increase in foreign demand reduces long maturity forward rates.

Is Foreign Demand/Personal Income Exogenous? Simultaneity is a standard problem in econometrics. Equation (1) specifies that weekly Official International Transactions scaled by monthly Personal Income affects the daily forward rate. But if the daily forward rate affects weekly Official International Transactions scaled by monthly Personal

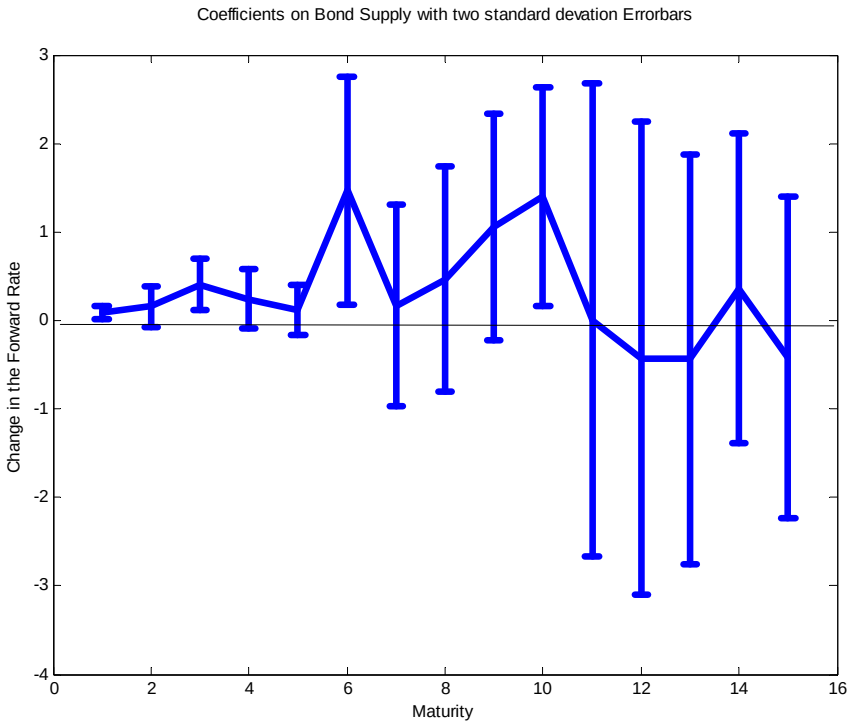

Figure 4: Change in the Forward rate (%) for maturities $n = 1$ to $n = 15$, from Foreign Bond Supply with their two standard deviation errorbars.

Income we have a simultaneous equation system. This seems unlikely based on the economics and the data frequency. It is possible, but unlikely, that foreign Central Banks reoptimize their portfolio of exchange holdings daily to take advantage of changes in bond prices. To correct for possible simultaneous bias we instrument oit_t with oit lagged five and twenty periods. Five periods means that the Official International Transactions are from the previous week, that is predetermined, and twenty periods mean that Personal Income is from the previous month. The coefficient estimates, not reported here, are virtually the same.

Bond Supply In theory an increase in the supply of a bond of a particular maturity should decrease the price unless a bond of another maturity is a perfect substitute. Figure 4 shows the estimated coefficients with two standard error bars on the supply of Treasuries by maturity.

An increase in the supply of maturity n increases the forward rate $f(n)$, and decreases

the price. The coefficients on only the one, three, six, and ten year maturities are significant at the 5% level. The empirical evidence that bond supply affects the price is suggestive, but not strong. Possibly the fact that our bond supply series are monthly masks their impact on daily forward rates. In an event study Bernanke, Reinhart, and Sack (2004) found that Japanese Central Bank purchases of US bonds are correlated significantly with yield reductions on the two, five, and ten year maturity bonds.

Macroeconomic Surprises: Surprises in Consumer Confidence, Index of Business Activity (NAPM) , Nonfarm Payroll, New Home Sales, and Retail Sales significantly affect all forward rates so they could explain the conundrum. GSS (2005) get similar results. Figure 5 shows the estimated coefficients with two standard deviation error bars for the extreme patterns.

A surprise in nonfarm payroll affects short maturity forward rates more than long maturity rates. In the lexicon of Litterman and Schienkman (1991), a Nonfarm Payroll surprise is a slope factor as it twists the slope of the yield curve. A positive surprise in New Home Sales lifts forward rates for all maturities by roughly the same amount. New Home Sales are a level factor. The pattern of the other macro factor coefficients fall in between the Nonfarm Payroll coefficients and the New Home Sales coefficients.[10]

4.1.2 Factors that Cannot Explain the Conundrum

Money, capacity utilization and CPI surprises significantly affect short maturity factors, slope factors, but have no significant effect on longer, six years and greater, forward rates. GDP surprises have no significant effect on forward rates. These factors can not explain the conundrum.

4.2 Calculation of the Marginal Cumulative Impact of a Factor

Here we calculate the cumulative marginal impact of factors that could explain the conundrum. We decompose the forward rate into a portion due to changes in the factors plus the value that the forward rate would have equaled if the factors had not changed.

Rewrite equation (1) in more compact notation as

$$f(n)_t = a(n)f(n)_{t-1} + \beta(n)'z_t + e(n)_t, \tag{2}$$

[10] In the yield curve literature usually the factors are unobservable and normalized so that the coefficients can be interpreted as the response to a one-standard deviation surprise. The macro factors are observable and not scaled so that one cannot compare meaningfully the magnitude of the coefficents across factors.

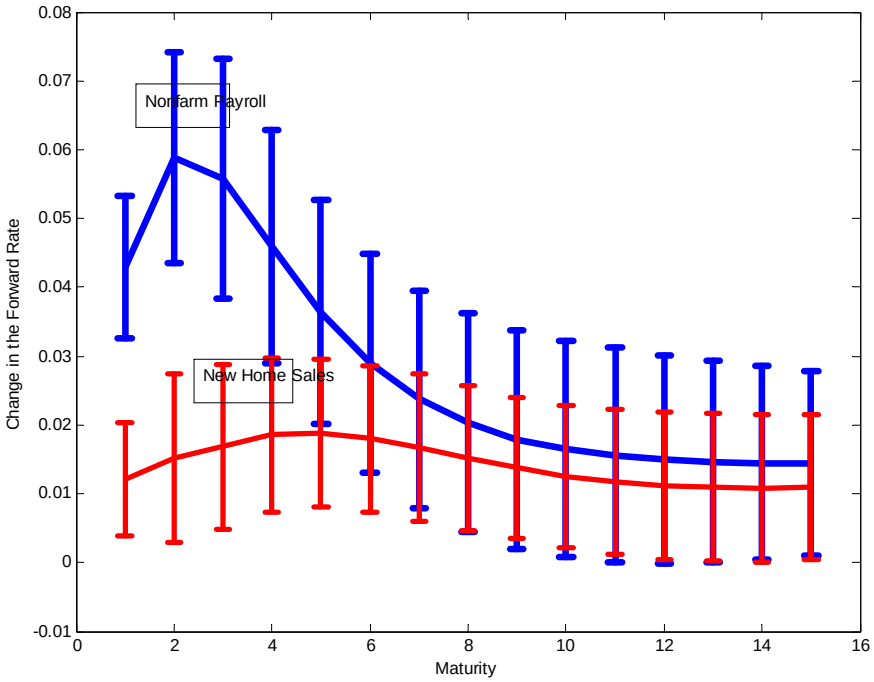

Figure 5: Change in the Forward rate (%) for maturities $n = 1$ to $n = 15$, from the macro surprise variables Nonfarm Payroll and New Home Sales, with their two standard deviation errorbars.

where $\beta(n)'z_t$ is the coefficient vector on the factors including the constant, times the factor vector. Solving the difference equation forward

$$f(n)_{t+k} = \sum_{j=0}^{k} a(n)^j \left(\beta(n)'z_{t+k-j} + e(n)_{t+k-j}\right) + a(n)^{k+1} f(n)_{t-1}, \tag{3}$$

expresses the forward rate for period $t+k$ as the cumulative effect of the exogenous factors plus the error (first term) plus the decayed value of the initial condition (second term). To isolate the cumulative marginal impact of the factors over the period t to $t+k$, subtract and add $\sum_{j=0}^{k} a(n)^j(\beta(n)'z_t$ to equation (3). Rearranging gives

$$\begin{aligned} f(n)_{t+k} &= \sum_{j=0}^{k} a(n)^j \beta(n)' \Delta z_{t+k-j} \\ &\quad + \left[a(n)^{k+1} f(n)_{t-1} + \sum_{j=0}^{k} a(n)^j \beta(n)' z_t + \sum_{j=0}^{k} a(n)^j e(n)_{t+k-j} \right], \end{aligned} \tag{4}$$

where $\Delta z_{t+k} \equiv z_{t+k} - z_t$. The first term on the right-hand side of equation (4) gives the cumulative impact of changes in the factors over the period from t to $t+k$, on the forward rate in period $t+k$. The second term, the term in brackets, gives the forward rate for $t+k$ evaluated by setting the factors at period $t+j$ to the initial values, i.e., $z_{t+j} = z_t$, i.e., it gives the value of the forward rate if the factors had stayed constant.

To explain the conundrum the change in the forward rate due to the change in the factor, the first term on the right-hand side of equation (4), call it a differential

$$df(n)_{z,t+k} \equiv \sum_{j=0}^{k} a(n)^j \beta(n)' \Delta z_{t+k-j}, \tag{5}$$

must be large and negative.

Impact of Foreign Demand and the Supply of Ten Year Bonds on the Ten Year Forward Rate For each day from 1/2/2004 to 8/6/2006 we calculated the cumulative marginal impact of the change in foreign demand on the ten year forward rate. And we calculated the cumulative marginal impact of the change in the supply of Treasury bonds with ten year maturities. Figure 6 shows the impact of the change in foreign demand (labeled DF10_OIT) and the impact of the change in foreign demand plus the impact of the change in supply (labeled DF10_OIT + DF10_TR10). To give perspective Figure 6 also plots the change in the ten year forward rate from its value at the beginning of 2004 (labeled F10(t) - F10(o)).

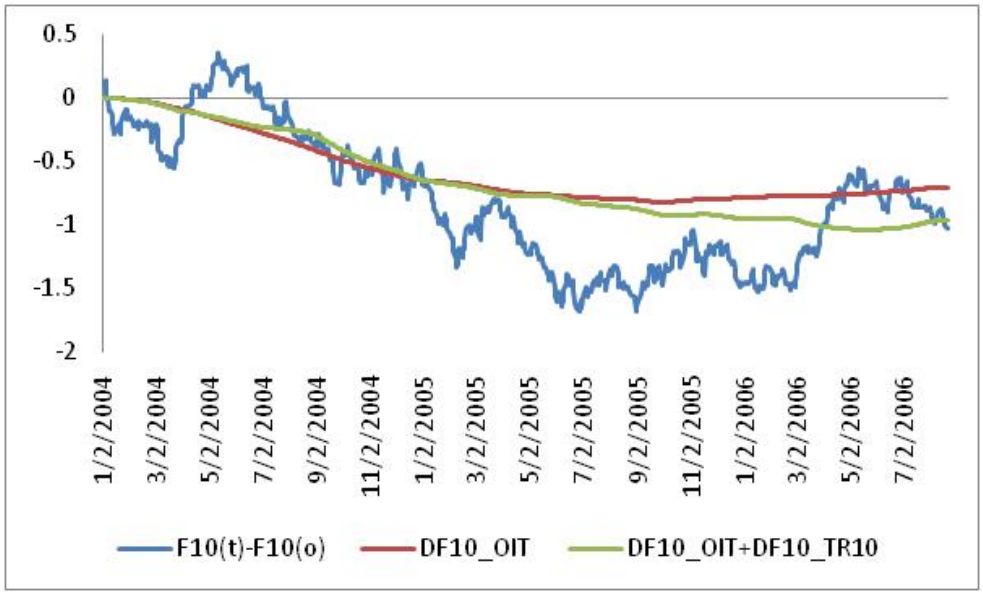

Figure 6: The cumulative change in the ten year forward rate (F10(t) - F10(o)) from 2004 to 2006 (%), and the impact on the ten year forward rate of the change in foreign demand (DF10_OIT) and the impact of the change in foreign demand plus the daily cumulative marginal impact of the change in supply (DF10_OIT + DF10_TR10).

From 2004 until Greenspan's conundrum testimony on February 16, 2005 the Fed increased the Target by 1.5% and the ten year forward rate fell by 1.17%. During the same period the holdings of US Treasury Debt by foreign central banks grew by 24%. Our calculations show that the increased foreign demand reduced the ten year forward rate by 0.67%. In 2005 the foreign holdings relative to personal income leveled out, see Figure 2, and the cumulative marginal impact of foreign holdings on the ten year forward rate levels out at about -0.8%.[11] Our calculations are remarkably close to Warnock & Warnock's estimate that foreign demand reduced ten year bond yield by 90 basis points in 2005. The supply of ten year bonds relative to personal income began to fall in the second half of 2005 as the economy recovered and our calculations show that the fall in supply also put some downward pressure on the forward rate peaking at about 0.25%.

[11] A referree suggested that we scale foreign holdings by the stock of outstanding Treasury debt instead of Personal Income. We did. The regression coefficient estimates on the impact of the rescaled foreign holdings have a p value of 0.001. And the cummulative marginal impact is 0.7% instead of 0.8% in Figure 2. The results are robust with respect to the scaling factor.

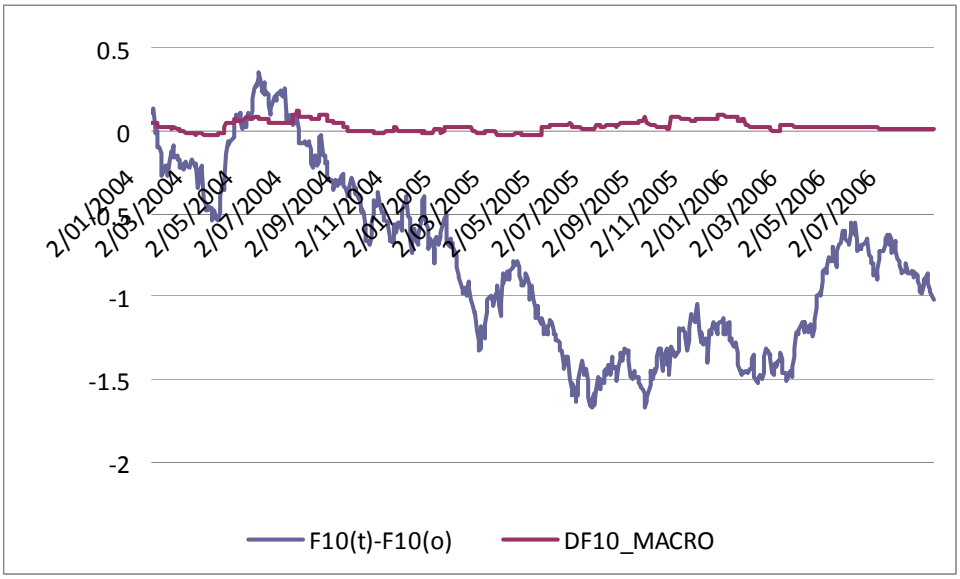

Figure 7: The cumulative change in the ten year forward rate (F10(t) - F10(o)) from 2004 to 2006 (%), and the joint impact on the ten year forward rate of the macroeconomic surprise variables (DF(10)_MACRO).

The Macroeconomic Factors The cumulative marginal effect of the macroeconomic factors is small, usually less than 0.1%, and usually positive. Figure 7 shows the impact of the macro factors on the ten year forward rate (labeled DF10_MACRO) and the change in the ten year forward rate from the beginning of 2004 through 2006 (labeled F10(t) - F10(o)).

The cumulative marginal impact of the macroeconomic surprises is too small to explain changes in the forward rates (or yields).[12]

5 Conclusions

When the Fed gradually raised the Target from 1% in 2004 to 5 1/4% in 2006, short rates dutifully followed the Target up, but long maturity rates actually fell. Greenspan labeled the strange behavior a conundrum. This paper examined whether or not exogenous economic factors that drive yields could explain the conundrum. We found that the increase in foreign demand for US Treasury bonds reduced ten year forward rates by at least 0.5% below what they would have been if foreign demand had not increased after 2003. That explains most of the conundrum.

[12] Appendix B shows that macroeconomic surprises cannot explain the conundrum even when we specify that forward rates have a unit root so that surprises have permanent effects.

The results are intuitive and empirically robust. In traditional asset pricing models an increase in demand for a bond raises its price and lowers its yield. Foreign demand for marketable long maturity (over one year) Treasury debt grew rapidly over the conundrum period: according to the TIC annual survey, in June of 2003 foreigners owned 46% of long maturity Treasury debt which increased to 57% by June of 2007. To quantify the effect on yields, actually forward rates, we added foreign demand and the supply of Treasury debt to a mean reverting model in which forward rates are driven by monetary and macroeconomic surprises. The coefficients on foreign demand are large and significant. The increase in foreign demand reduced long maturity forward rates. The results are robust. Appendix B shows that a vector error correction model gives essentially the same results as the mean reverting specification.

Foreign official holdings of US Treasuries as a fraction of US Personal Income seem to have plateaued in 2005, see Figure 2. If foreigners continue to hold over half of the long maturity US Treasury debt it will keep long maturity rates low. On the other hand, if they choose to rebalance their portfolios and hold less US dollar denominated debt it would mean higher long maturity rates and put more pressure on the dollar to depreciate.

A Mean Reversion Model Results

Table A1:
Parameter estimates of (1) for $n = 1$ to 5 year maturities: p-values in parentheses.

Explanatory Variables	Dependent Variable				
	$y\,(1)$	$f\,(2)$	$f\,(3)$	$f\,(4)$	$f\,(5)$
Lagged Dep. Variable	0.999	0.999	0.996	0.997	0.997
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Foreign Holdings of US	0.046	-0.023	-0.144	-0.152	-0.172
Treasury Securities	(0.374)	(0.770)	(0.125)	(0.147)	(0.104)
Supply of Treasury Debt	0.087	0.156	0.407	0.241	0.119
by Maturity	(0.022)	(0.173)	(0.005)	(0.149)	(0.400)
Money	0.004	0.003	0.001	0.001	0.000
	(0.000)	(0.001)	(0.223)	(0.605)	(0.835)
Capacity Utilization	0.013	0.021	0.023	0.017	0.013
	(0.000)	(0.000)	(0.000)	(0.001)	(0.016)
Consumer Confidence	0.017	0.025	0.028	0.028	0.026
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Consumer Price Index	0.017	0.023	0.025	0.021	0.018
	(0.000)	(0.000)	(0.000)	(0.001)	(0.002)
Advance GDP	0.013	0.019	0.009	0.003	0.003
	(0.069)	(0.096)	(0.520)	(0.814)	(0.821)
Index of Business	0.029	0.042	0.047	0.045	0.041
Activity	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Nonfarm Payroll	0.043	0.059	0.056	0.046	0.036
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
New Home Sales	0.012	0.015	0.017	0.019	0.019
	(0.004)	(0.013)	(0.005)	(0.001)	(0.001)
Retail Sales	0.022	0.028	0.029	0.024	0.020
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
Constant	-0.018	-0.005	0.015	0.020	0.027
	(0.014)	(0.572)	(0.144)	(0.095)	(0.052)
$\overline{R}^2$	0.999	0.999	0.998	0.997	0.997
σ	0.046	0.066	0.072	0.070	0.068

Table A2:
Parameter estimates of (1) for $n = 6$ to 10 year maturities: p-values in parentheses.

Explanatory Variables	Dependent Variable				
	$f(6)$	$f(7)$	$f(8)$	$f(9)$	$f(10)$
Lagged Dep. Variable	0.995	0.996	0.996	0.994	0.992
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Foreign Holdings of US	-0.054	-0.230	-0.306	-0.408	-0.478
Treasury Securities	(0.666)	(0.046)	(0.009)	(0.002)	(0.000)
Supply of Treasury Debt	1.470	0.169	0.466	1.054	1.397
by Maturity	(0.022)	(0.767)	(0.465)	(0.101)	(0.023)
Money	0.000	0.000	0.000	-0.001	-0.001
	(0.977)	(0.789)	(0.605)	(0.456)	(0.320)
Capacity Utilization	0.010	0.009	0.008	0.008	0.008
	(0.066)	(0.128)	(0.166)	(0.172)	(0.172)
Consumer Confidence	0.024	0.022	0.02	0.019	0.017
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Consumer Price Index	0.015	0.012	0.01	0.008	0.007
	(0.007)	(0.022)	(0.064)	(0.142)	(0.208)
Advance GDP	0.004	0.005	0.005	0.005	0.004
	(0.716)	(0.657)	(0.626)	(0.597)	(0.649)
Index of Business	0.036	0.031	0.027	0.024	0.021
Activity	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Nonfarm Payroll	0.029	0.024	0.020	0.018	0.017
	(0.000)	(0.003)	(0.010)	(0.024)	(0.035)
New Home Sales	0.018	0.017	0.015	0.014	0.012
	(0.001)	(0.002)	(0.004)	(0.008)	(0.016)
Retail Sales	0.018	0.016	0.015	0.014	0.014
	(0.004)	(0.009)	(0.013)	(0.015)	(0.014)
Constant	0.020	0.039	0.047	0.062	0.076
	(0.233)	(0.014)	(0.004)	(0.001)	(0.000)
$\overline{R}^2$	0.997	0.997	0.997	0.996	0.996
σ	0.066	0.065	0.065	0.065	0.065

Table A3:
Parameter estimates of (1) for $n = 11$ to 15 year maturities: p-values in parentheses.

Explanatory Variables	Dependent Variable				
	$f(11)$	$f(12)$	$f(13)$	$f(14)$	$f(15)$
Lagged Dep. Variable	0.995	0.995	0.995	0.996	0.996
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Foreign Holdings of US	-0.298	-0.305	-0.286	-0.247	-0.260
Treasury Securities	(0.006)	(0.007)	(0.006)	(0.013)	(0.013)
Supply of Treasury Debt	0.005	-0.428	-0.434	0.363	-0.414
by Maturity	(0.997)	(0.749)	(0.708)	(0.679)	(0.648)
Money	-0.001	-0.001	-0.001	-0.001	-0.001
	(0.275)	(0.256)	(0.262)	(0.322)	(0.404)
Capacity Utilization	0.008	0.008	0.008	0.008	0.008
	(0.144)	(0.125)	(0.110)	(0.098)	(0.098)
Consumer Confidence	0.016	0.015	0.014	0.014	0.013
	(0.001)	(0.004)	(0.010)	(0.018)	(0.029)
Consumer Price Index	0.007	0.007	0.008	0.010	0.012
	(0.238)	(0.218)	(0.152)	(0.083)	(0.032)
Advance GDP	0.004	0.003	0.002	0.001	0.000
	(0.689)	(0.762)	(0.837)	(0.924)	(0.980)
Index of Business	0.019	0.018	0.017	0.017	0.017
Activity	(0.001)	(0.003)	(0.003)	(0.002)	(0.001)
Nonfarm Payroll	0.016	0.015	0.015	0.015	0.014
	(0.045)	(0.048)	(0.046)	(0.039)	(0.031)
New Home Sales	0.012	0.011	0.011	0.011	0.011
	(0.026)	(0.036)	(0.042)	(0.043)	(0.036)
Retail Sales	0.013	0.013	0.013	0.012	0.011
	(0.016)	(0.016)	(0.017)	(0.019)	(0.022)
Constant	0.055	0.057	0.054	0.049	0.051
	(0.001)	(0.001)	(0.001)	(0.002)	(0.004)
$\overline{R}^2$	0.997	0.996	0.996	0.996	0.996
σ	0.065	0.064	0.064	0.062	0.061

B Error Correction Model Results

Daily forward rates and yields are highly autocorrelated and fail to reject unit root tests. This could lead to inference problems even if the rates are stationary. This appendix presents results from a specification that assumes the ten and five year forward rates, $f(10)$ and $f(5)$, have unit roots and that they are cointegrated. The data do not reject this specification. The empirical results are remarkably similar to the empirical results for the mean reverting specification in the paper and in Appendix A.

The results from the cointegration model show that:

- forward rates are cointegrated – this confirms the well known results that yields move together;
- the dynamics are captured by the error correction term which is consistent with our mean-reverting specification with one lag;
- foreign demand explains about 1/2 of the decline in the ten year forward rate. This is less than the mean-reverting result that says that foreign demand explains about 2/3 of the decline in the ten year forward rate. Either specification shows that foreign demand had a large and significant impact on long maturity rates;
- the macroeconomic surprises that are significant in the mean-reverting equation for the ten-year forward rate are also exactly the surprises that are significant in the cointegrated model;
- monetary and macroeconomic surprises cannot explain the decline in the ten year forward rate in either specification.

Table B1 gives the results of testing for cointegration between $f(10)_t$ and $f(5)_t$ using a bivariate vector error-correction model (VECM) with 2 lags.[13] The choice of 2 lags does not qualitatively change the empirical results. The sample period runs from the beginning of 1990 until the end of 2004, prior to the conundrum period. Included in the VECM are the foreign demand and supply variables, the money shock variable and the eight macroeconomic shock variables, which are all treated exogenously. The p-values of the cointegration test are not adjusted to allow for the inclusion of the exogenous variables. The results of the cointegration test show that there is one cointegrating vector between the two variables at the 5% level.

The estimates of the cointegrating vector are given in Table B2.

[13] Unit root tests applied to $f(5)_t$ and $f(10)_t$, provide evidence of a unit root at conventional significance levels.

Table B.3 gives the estimates of the bivariate system with exogenous driving variables. The parameter estimate on the error-correction term in the 5-year forward yield equation is statistically insignificant, providing evidence that this variable is weakly exogenous. Moreover, the lagged changes in the 10-year forward rate in this equation are also statistically insignificant showing that the 5 year forward rate is strongly exogenous with respect to the 10-year forward rate. The pattern of significance of macroeconomic and monetary surprises matches exactly the mean-reverting results for the ten year forward rate in Table A.2.

Table B1:
Cointegation test results for $n = 5$ and 10 year maturities.

Hypotheses	Eigenvalue	Trace Statistic	Critical Value (5%)	P-value
None	0.006	28.227	20.262	0.003
At most one	0.002	7.748	9.164	0.092

Table B2:
Cointegation parameter estimates for $n = 5$ and 10 year maturities.

Explanatory Variables	Dependent Variable: $f(10)_t$		
	Estimate	Std error	P-value
Constant	6.235	0.949	0.000
$f(5)_t$	0.419	0.097	0.000

Table B3:
Bivariate vector error correction parameter estimates for $n = 5$ and 10 year maturities.

Explanatory Variables	Dependent Variables					
	$f(10)_t - f(10)_{t-1}$			$f(5)_t - f(5)_{t-1}$		
	Est.	Std. error	P-value	Est.	Std. error	P-value
Error correction lagged	-0.011	0.003	0.002	-0.002	0.003	0.505
$f(10)_{t-1} - f(10)_{t-2}$	0.010	0.024	0.677	0.017	0.026	0.513
$f(10)_{t-2} - f(10)_{t-3}$	-0.034	0.024	0.156	-0.008	0.025	0.749
$f(5)_{t-1} - f(5)_{t-2}$	0.013	0.023	0.572	0.047	0.024	0.050
$f(5)_{t-2} - f(5)_{t-3}$	0.036	0.023	0.117	-0.016	0.024	0.505
Foreign Holdings of US Treasury Securities	-0.407	0.125	0.001	-0.095	0.131	0.468
Supply of Treasury Debt by Maturity	0.924	0.473	0.051	0.233	0.493	0.636
Money	-0.001	0.001	0.317	0.001	0.001	0.317
Capacity Utilization	0.008	0.005	0.110	0.013	0.005	0.009
Consumer Confidence	0.017	0.005	0.001	0.025	0.005	0.000
Consumer Price Index	0.007	0.005	0.161	0.018	0.005	0.001
Advance GDP	0.004	0.009	0.657	0.003	0.009	0.739
Index of Business Activity	0.020	0.005	0.000	0.040	0.005	0.000
Nonfarm Payroll	0.016	0.005	0.001	0.036	0.005	0.000
New Home Sales	0.013	0.006	0.030	0.019	0.006	0.002
Retail Sales	0.014	0.006	0.020	0.020	0.006	0.001

B.1 Calculation of the Marginal Cumulative Impact of a Factor

We calculate the marginal cumulative impact of a factor in the cointegration specification using the vector analogue to equation (4) in Section 4.

The bivariate error correction model in Table B.3 is

$$\Delta f_t = \alpha.[f(10)_{t-1} - c_0 - bf(5)_{t-1}] + \gamma_1 \Delta f_{t-1} + \gamma_2 \Delta f_{t-2} + Bz_t + e_t, \tag{6}$$

where f is the (2×1) vector of the ten and five year forward rates and the term in brackets [] is the cointegrating vector in Table B.2, z is the vector of the exogenous driving variables and e is the error vector. Rewriting equation (6) in levels and dropping the insignificant lags in Table B.3 gives

$$f_t = Af_{t-1} + Bz_t + e_t. \tag{7}$$

Equation (7) is the vector analogue of equation (1). Following the same steps as in Section 4 gives the "differential"

$$df_{z,t+k} = \sum_{j=0}^{k} A^j B \Delta z_{t+k-j}, \tag{8}$$

where $\Delta z_{t+k} \equiv z_{t+k} - z_t$.

B.1.1 Impact of Foreign Demand and the Supply of Ten Year Bonds on the Ten Year Forward Rate

Figure 8 shows cumulative marginal impact of the change in foreign demand and the supply of ten year Treasury securities on the ten year forward rate from 2004-2006. Figure 8 is the analogue to Figure 6 in the paper. Figure 8 shows the impact of the change in foreign demand (labeled DF10(coint)_OIT) and the impact of the change in foreign demand plus the impact of the change in supply (labeled DF10(coint)_OIT + DF10(coint)_TR10). To give perspective Figure 8 also plots the cumulative change in the ten year forward rate from the beginning of 2004 through 2006 (labeled F10(t) - F10(o)).

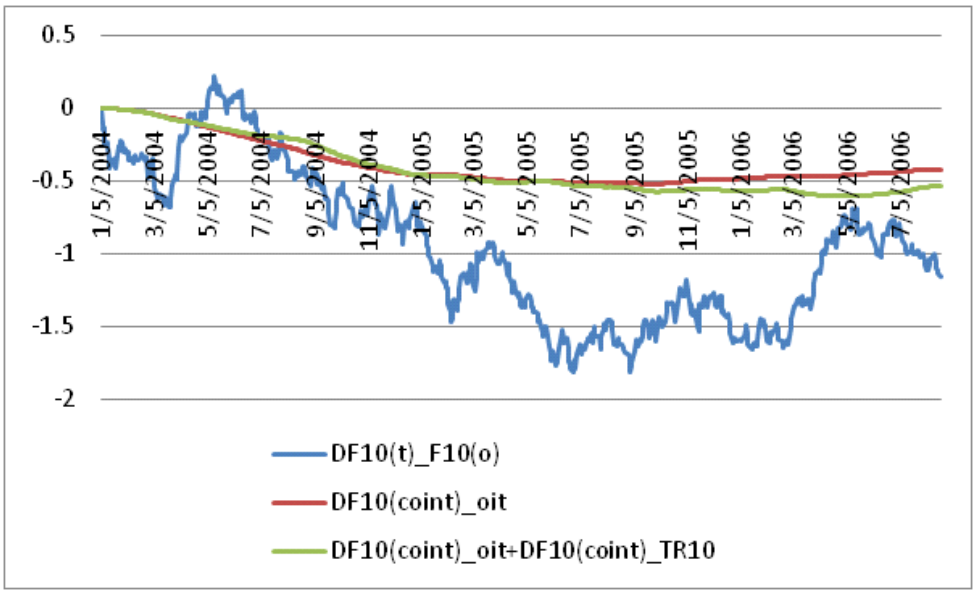

Figure 8: Error correction results. The cumulative change in the ten year forward rate (F10(t) - F10(o)) from 2004 to 2006 (%), and the impact on the ten year forward rate of the change in foreign demand (DF10(coint)_OIT) and the impact of the change in foreign demand plus the daily cumulative marginal impact of the change in supply (DF10_OIT(coint) + DF10(coint)_TR10).

From 2004 until Greenspan's conundrum testimony on February 16, 2005 the Fed increased the Target by 1.5% and the ten year forward rate fell by 1.17%. During the same period the holdings of US Treasury Debt by foreign central banks grew by 24%. Using the cointingration specification our calculations show that the increased foreign demand reduced the ten year forward rate by about 0.47%. In 2005 the foreign holdings relative to personal income leveled out, see Figure 2, and the cumulative marginal impact of foreign holdings on the ten year forward rate in the cointegration specification levels out at about -0.5%.

Our empircal results for the cointegration specification attribute roughly 1/2 the decline in the ten-year forward rate to the increase in foreign demand. In the mean-reverting specification we attributed 2/3 of the decline in the ten-year forward rate to the increase in foreign demand. Either specification says that most of the conundrum is explained by the increased foreign holdings of US Treasury debt.

The supply of ten-year Treasuries has a similar role in the vector error correction results as it does in the mean reversion results. It has a small, but statistically significant, impact in the mean-reverting specification.

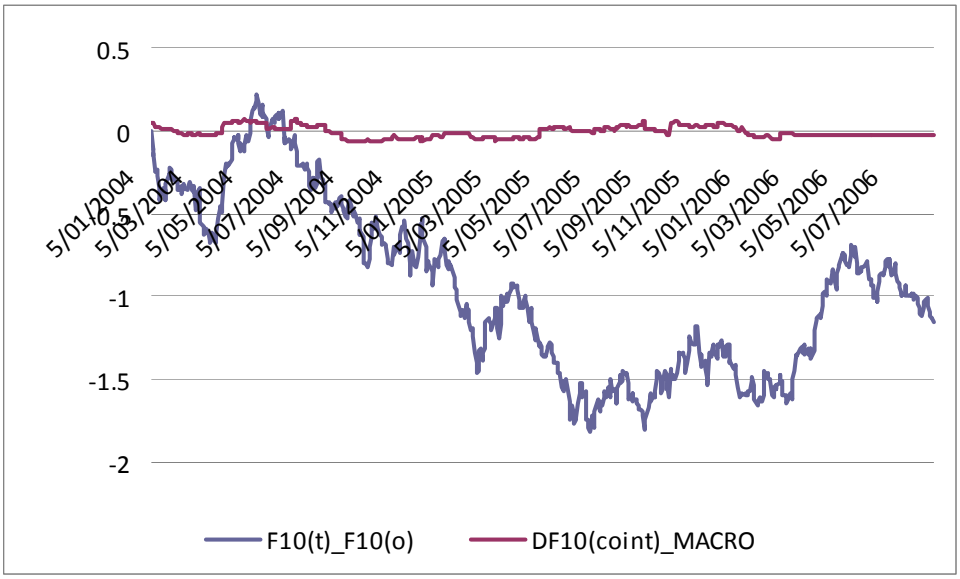

Figure 9: Error correction results. The cumulative change in the ten year forward rate (F10(t) - F10(o)) from 2004 to 2006 (%), and the joint impact on the ten year forward rate of the macroeconomic surprise variables (DF10(coint)_MACRO).

B.1.2 The Macroeconomic Factors

Figure 9 shows cumulative marginal impact of the macroeconomic surprises on the ten year forward rate.Figure 9 is the analogue to Figure 7 in the paper. Figure 9 shows the cumulative impact of macroeconomic surprises (labeled DF10(coint)_MACRO) on the ten year forward rate. To give perspective Figure 9 also plots the cumulative change in the ten year forward rate from the beginning of 2004 through 2006 (labeled F10(t) - F10(o)).

The macroeconomic surprises have statistically significant impacts on the forward rate, but the cummulative effect is small. Macroeconomic surprises do not explain the conundrum.

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