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# **Can Information Heterogeneity Explain the Exchange Rate Determination Puzzle?**

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# Can Information Heterogeneity Explain the Exchange Rate Determination Puzzle? <sup>1</sup>

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## **Abstract**

Empirical evidence shows that observed macroeconomic fundamentals have little explanatory power for nominal exchange rates (the exchange rate determination puzzle). On the other hand, the recent “microstructure approach to exchange rates” has shown that most exchange rate volatility at short to medium horizons is related to order flow. In this paper we introduce symmetric information dispersion about future fundamentals in a dynamic rational expectations model in order to explain these stylized facts. Consistent with the evidence the model implies that (i) observed fundamentals account for little of exchange rate volatility in the short to medium run, (ii) over long horizons the exchange rate is closely related to observed fundamentals, (iii) exchange rate changes are a weak predictor of future fundamentals, and (iv) the exchange rate is closely related to order flow over both short and long horizons.

# I Introduction

The poor explanatory power of existing theories of the nominal exchange rate is most likely the major weakness of international macroeconomics. Meese and Rogoff [1983] and the subsequent literature have found that a random walk predicts exchange rates better than macroeconomic models in the short run. Lyons [2001] refers to the weak explanatory power of macroeconomic fundamentals as the “exchange rate determination puzzle”.<sup>1</sup> This puzzle is less acute for long-run exchange rate movements, since there is extensive evidence of a much closer relationship between exchange rates and fundamentals at horizons of two to four years (e.g., see Mark [1995]). Recent evidence from the microstructure approach to exchange rates suggests that investor heterogeneity might play a key role in explaining exchange rate fluctuations. In particular, Evans and Lyons [2002a] show that most short-run exchange rate volatility is related to order flow, which in turn is associated with investor heterogeneity.<sup>2</sup> Since these features are not present in existing theories, a natural suspect for the failure of current models to explain exchange rate movements is the standard hypothesis of a representative agent.

The goal of this paper is to present an alternative to the representative agent model that can explain the exchange rate determination puzzle and the evidence on order flow. We introduce heterogenous information into a standard dynamic monetary model of exchange rate determination. There is a continuum of investors who differ in two respects. First, they have symmetrically dispersed information about future macroeconomic fundamentals.<sup>3</sup> Second, they face different exchange rate risk exposure associated with non-asset income. This exposure is private information and leads to hedge trades whose aggregate is unobservable. Our main finding is that information heterogeneity disconnects the exchange rate from observed

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<sup>1</sup>See Cheung et.al. [2002] for more recent evidence. The exchange rate determination puzzle is part of a broader set of exchange rate puzzles that Obstfeld and Rogoff [2001] have called the “exchange rate disconnect puzzle”. This also includes the lack of feedback from the exchange rate to the macro economy and the excess volatility of exchange rates (relative to fundamentals).

<sup>2</sup>See also Rime [2001], Froot and Ramadorai [2002], Evans and Lyons [2002b] or Hau et al. [2002].

<sup>3</sup>We know from extensive survey evidence that investors have different views about the macroeconomic outlook. There is also evidence that exchange rate expectations differ substantially across investors. See Chionis and MacDonald [2002], Ito [1990], Elliott and Ito [1999], and MacDonald and Marsh [1996].

macroeconomic fundamentals in the short run, while there is a close relationship in the long run. At the same time there is a close link between the exchange rate and order flow over all horizons.

Our modeling approach integrates several strands of literature. First, it has in common with most of the existing (open economy) macro literature that we adopt a fully dynamic general equilibrium model, leading to time-invariant second moments. Second, it has in common with the noisy rational expectations literature in finance that the asset price (exchange rate) aggregates private information of individual investors, with unobserved shocks preventing average private signals from being fully revealed by the price. The latter are modeled endogenously as hedge trades in our model.<sup>4</sup> Third, it has in common with the microstructure literature of the foreign exchange market that private information is transmitted to the market through order flow.<sup>5</sup>

Most models in the noisy rational expectations literature and microstructure literature are static or two-period models.<sup>6</sup> This makes them ill-suited to address the disconnect between asset prices and fundamentals, which has a dynamic dimension since the disconnect is much stronger at short horizons. Even the few dynamic rational expectation models in the finance literature cannot be applied in our context. Wang [1993, 1994] develops an infinite horizon noisy rational expectations model. There are only two types of investors, one of which can fully observe the variables affecting the equilibrium asset price. We believe that it is more appropriate to consider cases where no class of investors has superior information and where there is broader dispersion of information. Several papers make a step in this direction by examining symmetrically dispersed information in a multi-period model, but they only examine an asset with a single payoff at a terminal date.<sup>7</sup>

For the dynamic dimension of our paper, we rely on the important paper by

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<sup>4</sup>Some recent papers in the exchange rate literature have introduced exogenous noise in the foreign exchange market. However, they do not consider information dispersion about future macro fundamentals. Examples are Hau [1998], Jeanne and Rose [2002], Devereux and Engel [2002], Kollman [2002], and Mark and Wu [1998].

<sup>5</sup>See Lyons [2001] for an overview of this literature.

<sup>6</sup>See Brunnermeier [2001] for an overview.

<sup>7</sup>See He and Wang [1995], Vives [1995], Foster and Viswanathan [1996] or Brennan and Cao [1997]. The latter assume that private information is symmetrically dispersed among agents within a country, while there is also asymmetric information between countries.

Townsend [1983]. Townsend analyzed a business cycle model with symmetrically dispersed information. As is the case in our model, the solution exhibits infinitely higher order expectations (expectations of other agents' expectations).<sup>8</sup> We adapt Townsend's solution procedure to our model. The only application to asset pricing we are aware of is Singleton [1987], who applies Townsend's method to a model for government bonds with a symmetric information structure.<sup>9</sup>

The equilibrium price of our competitive noisy rational expectation model can be determined by a Walrasian auctioneer. However, the equilibrium can also be interpreted as the outcome of an order-driven auction market, whereby market orders based on private information hit an outstanding limit order book. This characterization resembles the electronic trading system that nowadays dominates the foreign exchange market. We define limit orders as orders that are conditional on public information, including the exchange rate. Limit orders provide liquidity to the market. Market orders take liquidity from the market and are associated with private information. Order flow is equal to net market orders. Private information is then transmitted to the market through order flow, while public information leads to price changes without any actual trade. Not surprisingly, the weak relationship in the model between short-run exchange rate fluctuations and publicly observed fundamentals is closely mirrored by the close relationship between exchange rate fluctuations and order flow.<sup>10</sup>

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<sup>8</sup>Subsequent contributions have been mostly technical, solving the same model as in Townsend [1983] with alternative methods. See Kasa [2000] and Sargent [1991]. Probably as a result of the technical difficulty in solving these models, the macroeconomics literature has devoted relatively little attention to heterogeneous information in the last two decades. This contrasts with the 1970s where, following Lucas [1972], there had been active research on rational expectations and heterogeneous information (e.g., see King, 1982). Recently, information issues in the context of price rigidity have again been brought to the forefront in contributions by Woodford [2003] and Mankiw and Reis [2002].

<sup>9</sup>In Singleton's model there is no information dispersion about the payoff structure on the assets (in this case coupons on government bonds), but there is private information about whether noise trade is transitory or persistent. The uncertainty is resolved after two periods.

<sup>10</sup>In recent work closely related to ours, Evans and Lyons [2004] also introduce microstructure features in a dynamic general equilibrium model in order to shed light on exchange rate puzzles. There are three important differences in comparison to our approach. First, they adopt a quote-driven market, while we model an order-driven auction market. Second, they assume that all investors within one country have the same information, while there is asymmetric information across countries. Third, their model is not in the noisy rational expectations tradition.

The dynamic implications of the model for the relationship between the exchange rate, observed fundamentals and order flow can be understood as follows. In the short run, rational confusion plays an important role in disconnecting the exchange rate from observed fundamentals. Investors do not know whether an increase in the exchange rate is driven by an improvement in average private signals about future fundamentals or an increase in unobserved hedge trades. This implies that unobserved hedge trades have an amplified effect on the exchange rate since they are confused with changes in average private signals about future fundamentals.<sup>11</sup> We show that a small amount of hedge trades can become the dominant source of exchange rate volatility when information is heterogeneous, while it has practically no effect on the exchange rate when investors have common information.

In the long run there is a close relationship between the exchange rate, observed fundamentals and cumulative order flow. First, rational confusion gradually dissipates as investors learn more about future fundamentals.<sup>12</sup> The impact of unobserved hedge trades on the equilibrium price therefore gradually weakens, leading to a closer long-run relationship between the exchange rate and observed fundamentals. Second, when the fundamental has a permanent component the exchange rate and cumulative order flow are closely linked in the long run. Private information about permanent future changes in the fundamental is transmitted to the market through order flow, so that order flow has a permanent effect on the exchange rate.

The remainder of the paper is organized as follows. Section II describes the model and solution method. Section III considers a special case of the model in order to develop intuition for our key results. Section IV discusses the implications of the dynamic features of the model. Section V presents numerical results based on the general dynamic model and Section VI concludes.

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<sup>11</sup>The basic idea of rational confusion can already be found in the noisy rational expectation literature. For example, Genotte and Leland [1990] and Romer [1993] argued that such rational confusion played a critical role in amplifying non-informational trade during the stock-market crash of October 19, 1987.

<sup>12</sup>Another recent paper on exchange rate dynamics where learning plays an important role is Gourinchas and Tornell [2004]. In that paper, in which there is no investor heterogeneity, agents learn about the nature of interest rate shocks (transitory or persistent), but there is an irrational misperception about the second moments in interest rate forecasts that never goes away.

## II A Monetary Model with Information Dispersion

### II.A Basic Setup

Our model contains the three basic building blocks of the standard monetary model of exchange rate determination: (i) money market equilibrium, (ii) purchasing power parity, and (iii) interest rate parity. We modify the standard monetary model by assuming incomplete and dispersed information across investors. Before describing the precise information structure, we first derive a general solution to the exchange rate under heterogeneous information, in which the exchange rate depends on higher order expectations of future macroeconomic fundamentals. This generalizes the standard equilibrium exchange rate equation that depends on common expectations of future fundamentals.

Both observable and unobservable fundamentals affect the exchange rate. The observable fundamental is the ratio of money supplies. We assume that investors have heterogeneous information about future money supplies. The unobservable fundamental takes the form of an aggregate hedge against non-asset income in the demand for foreign exchange. This unobservable element introduces noise in the foreign exchange market in the sense that it prevents investors from inferring average expectations about future money supplies from the price.<sup>13</sup> This trade also affects the risk premium in the interest parity condition.

There are two economies. They produce the same good, so that purchasing power parity holds:

$$p_t = p_t^* + s_t \tag{1}$$

Local currency prices are in logs and  $s_t$  is the log of the nominal exchange rate.

There is a continuum of investors in both countries on the interval  $[0,1]$ . We assume that there are overlapping generations of agents who live for two periods and make only one investment decision. This assumption significantly simplifies the presentation, helps in providing intuition, and allows us to obtain an exact solution to the model.<sup>14</sup>

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<sup>13</sup>For alternative modeling of 'noise' from rational behavior, see Wang [1994], Dow and Gorton [1995], and Spiegel and Subrahmanyam [1992].

<sup>14</sup>In an earlier version of the paper, Bacchetta and van Wincoop [2003], we also consider



Investors in both economies can invest in four assets: money of their own country, nominal bonds of both countries with interest rates  $i_t$  and  $i_t^*$ , and a technology with fixed real return  $r$  that is in infinite supply. We assume that one economy is large and the other infinitesimally small; variables from the latter are starred. Bond market equilibrium is therefore entirely determined by investors in the large country, on which we will focus. We also assume that money supply in the large country is constant. It is easy to show that this implies a constant price level  $p_t$  in equilibrium, so that  $i_t = r$ . For ease of notation, we just assume a constant  $p_t$ . Money supply in the small country is stochastic.

The wealth  $w_t^i$  of investors born at time  $t$  is given by a fixed endowment. At time  $t + 1$  these investors receive the return on their investments plus income  $y_{t+1}^i$  from time  $t + 1$  production. We assume that production depends both on the exchange rate and on real money holdings  $\widetilde{m}_t^i$  through the function  $y_{t+1}^i = \lambda_t^i s_{t+1} - \widetilde{m}_t^i (\ln(\widetilde{m}_t^i) - 1) / \alpha$ .<sup>15</sup> The coefficient  $\lambda_t^i$  measures the exchange rate exposure of the non-asset income of investor  $i$ . We assume that  $\lambda_t^i$  is time varying and known only to investor  $i$ . This will generate an idiosyncratic hedging term. Agent  $i$  maximizes

$$-E_t^i e^{-\gamma c_{t+1}^i}$$

subject to

$$c_{t+1}^i = (1 + i_t)w_t^i + (s_{t+1} - s_t + i_t^* - i_t)b_{Ft}^i - i_t \widetilde{m}_t^i + y_{t+1}^i$$

where  $b_{Ft}^i$  is invested in foreign bonds and  $s_{t+1} - s_t + i_t^* - i_t$  is the log-linearized excess return on investing abroad.

Combining the first order condition for money holdings with money market equilibrium in both countries we get

$$m_t - p_t = -\alpha i_t \tag{2}$$

$$m_t^* - p_t^* = -\alpha i_t^* \tag{3}$$

where  $m_t$  and  $m_t^*$  are the logs of domestic and foreign nominal money supply.

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an infinite-horizon version. While this significantly complicates the solution method, numerical results are almost identical.

<sup>15</sup>By introducing money through production rather than utility we avoid making money demand a function of consumption, which would complicate the solution.

The demand for foreign bonds by investor  $i$  is:<sup>16</sup>

$$b_{Ft}^i = \frac{E_t^i(s_{t+1}) - s_t + i_t^* - i_t}{\gamma\sigma_t^2} - b_t^i \quad (4)$$

where the conditional variance of next period's exchange rate is  $\sigma_t^2$ , which is the same for all investors in equilibrium. The hedge against non-asset income is represented by  $b_t^i = \lambda_t^i$ .

We assume that the exchange rate exposure is equal to the average exposure plus an idiosyncratic term, so that  $b_t^i = b_t + \varepsilon_t^i$ . We will only consider the limiting case where the variance of  $\varepsilon_t^i$  approaches infinity, so that knowing one's own exchange rate exposure provides no information about the average exposure. This assumption is only made for convenience. The results in the paper will not qualitatively change when we assume a finite, but positive, variance of  $\varepsilon_t^i$ . The key assumption is that the aggregate hedge component  $b_t$  is unobservable. We assume that the average exposure  $b_t$  follows an AR(1) process:

$$b_t = \rho_b b_{t-1} + \varepsilon_t^b \quad (5)$$

where  $\varepsilon_t^b \sim N(0, \sigma_b^2)$ . While  $b_t$  is an unobserved fundamental, the assumed autoregressive process is known by all agents.

## II.B Market Equilibrium and Higher Order Expectations

Since bonds are in zero net supply, market equilibrium is given by  $\int_0^1 b_{Ft}^i di = 0$ . One way to reach equilibrium is to have a Walrasian auctioneer to whom investors submit their demand schedule  $b_{Ft}^i$ . However, we show in the next section that the same equilibrium can also be implemented by introducing a richer microstructure in the form of an order-driven auction market. In that case we can relate the exchange rate to order flow.

Market equilibrium yields the following interest arbitrage condition:

$$\overline{E}_t(s_{t+1}) - s_t = i_t - i_t^* + \gamma\sigma_t^2 b_t \quad (6)$$

where  $\overline{E}_t$  is the average rational expectation across all investors. The model is summarized by (1), (2), (3), and (6). Other than the risk premium in the interest

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<sup>16</sup>Here we implicitly assume that  $s_{t+1}$  is normally distributed. We will see in section II.D that the equilibrium exchange rate indeed has a normal distribution.

rate parity condition associated with non-observable trade, these equations are the standard building blocks of the monetary model of exchange rate determination.

Defining the *observable* fundamental as  $f_t = (m_t - m_t^*)$ , in Appendix A we derive the following equilibrium exchange rate:

$$s_t = \frac{1}{1 + \alpha} \sum_{k=0}^{\infty} \left( \frac{\alpha}{1 + \alpha} \right)^k \bar{E}_t^k (f_{t+k} - \alpha \gamma \sigma_{t+k}^2 b_{t+k}) \quad (7)$$

where  $\bar{E}_t^0(x_t) = x_t$ ,  $\bar{E}_t^1(x_{t+1}) = \bar{E}_t(x_{t+1})$  and higher order expectations are defined as

$$\bar{E}_t^k(x_{t+k}) = \bar{E}_t \bar{E}_{t+1} \dots \bar{E}_{t+k-1}(x_{t+k}). \quad (8)$$

Thus, the exchange rate at time  $t$  depends on the fundamental at time  $t$ , the average expectation at  $t$  of the fundamental at time  $t + 1$ , the average expectation at  $t$  of the average expectation at  $t + 1$  of the fundamental at  $t + 2$ , etc. The law of iterated expectations does not apply to average expectations. For example,  $\bar{E}_t \bar{E}_{t+1}(s_{t+2}) \neq \bar{E}_t(s_{t+2})$ .<sup>17</sup> This is a basic feature of asset pricing under heterogeneous expectations: the expectation of other investors' expectations matters.<sup>18</sup> In a dynamic system, this leads to the infinite regress problem, as analyzed in Townsend [1983]: as the horizon goes to infinity the dimensionality of the expectation term goes to infinity.

## II.C The Information Structure

We assume that at time  $t$  investors observe all past and current  $f_t$ , while they receive private signals about  $f_{t+1}, \dots, f_{t+T}$ . More precisely, we assume that investors receive one signal each period about the observable fundamental  $T$  periods ahead. For example, at time  $t$  investor  $i$  receives a signal

$$v_t^i = f_{t+T} + \varepsilon_t^{vi} \quad \varepsilon_t^{vi} \sim N(0, \sigma_v^2) \quad (9)$$

<sup>17</sup>See Allen, Morris, and Shin [2003] and Bacchetta and van Wincoop [2004a].

<sup>18</sup>Notice that the higher order expectations are of a dynamic nature, i.e., today's expectations of tomorrow's expectations. This contrasts with most of the literature that considers higher order expectations in a static context with strategic externalities, e.g., Morris and Shin [2002] or Woodford [2003].

where  $\varepsilon_t^{vi}$  is independent from  $f_{t+T}$  and other agents' signals.<sup>19</sup> As usual in this context we assume that the average signal received by investors is  $f_{t+T}$ , i.e.,  $\int_0^1 v_t^i di = f_{t+T}$ .<sup>20</sup>

We also assume that the observable fundamental's process is known by all agents and consider a general process:

$$f_t = D(L)\varepsilon_t^f \quad \varepsilon_t^f \sim N(0, \sigma_f^2) \quad (10)$$

where  $D(L) = d_1 + d_2L + d_3L^2 + \dots$  and  $L$  is the lag operator. Since investors observe current and lagged values of the fundamental, knowing the process provides information about the fundamental at future dates.

## II.D Solution Method

In order to solve the equilibrium exchange rate there is no need to compute all the higher order expectations that it depends on. The key equation used in the solution method is the interest parity condition (6), which captures foreign exchange market equilibrium. It only involves a first order average market expectation. We adopt a method of undetermined coefficients, conjecturing an equilibrium exchange rate equation and then verifying that it satisfies the equilibrium condition (6). Townsend [1983] adopts a similar method for solving a business cycle model with higher order expectations.<sup>21</sup> Here we provide a brief description of the solution method, leaving details to Appendix B.

We conjecture the following equilibrium exchange rate equation that depends on shocks to observable and unobservable fundamentals:

$$s_t = A(L)\varepsilon_{t+T}^f + B(L)\varepsilon_t^b \quad (11)$$

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<sup>19</sup>This implies that each period investors have  $T$  signals that are informative about future observed fundamentals. Note that the analysis could be easily extended to the case where investors receive a vector of signals each period.

<sup>20</sup>See Admati [1985] for a discussion.

<sup>21</sup>The solution method described in Townsend [1983] applies to the model in section 8 of that paper where the economy-wide average price is observed with noise. Townsend [1983] mistakenly believed that higher order expectations are also relevant in a two-sector version of the model where firms observe each other's prices without noise. Pearlman and Sargent [2002] show that the equilibrium fully reveals private information in that case.

where  $A(L)$  and  $B(L)$  are infinite order polynomials in the lag operator  $L$ . The errors  $\varepsilon_t^{iv}$  do not enter the exchange rate equation as they average to zero across investors. Since at time  $t$  investors observe the fundamental  $f_t$ , only the innovations  $\varepsilon^f$  between  $t+1$  and  $t+T$  are unknown. Similarly shocks  $\varepsilon^b$  between  $t-T$  and  $t$  are unknown. Exchange rates at time  $t-T$  and earlier, together with knowledge of  $\varepsilon^f$  at time  $t$  and earlier, reveal the shocks  $\varepsilon^b$  at time  $t-T$  and earlier.

Investors can then solve a signal extraction problem for the finite number of unknown innovations. Both private signals and exchange rates from time  $t-T+1$  to  $t$  provide information about the unknown innovations. The solution to the signal extraction problem leads to expectations at time  $t$  of the unknowns as a function of observables, which in turn can be written as a function of the innovations themselves. One can then compute the average expectation of  $s_{t+1}$ . Substituting the result into the interest parity condition (6) leads to a new exchange rate equation. The coefficients of the polynomials  $A(L)$  and  $B(L)$  can then be derived by solving a fixed point problem, equating the coefficients of the conjectured exchange rate equation to those in the equilibrium exchange rate equation. Although the lag polynomials are of infinite order, for lags longer than  $T$  periods the information dispersion plays no role and an analytical solution to the coefficients is feasible.<sup>22</sup>

### III Model Implications: A Special Case

In this section we examine the special case where  $T = 1$ , which has a relatively simple solution. This example is used to illustrate how information heterogeneity disconnects the exchange rate from observed macroeconomic fundamentals, while establishing a close relationship between the exchange rate and order flow.

One aspect that simplifies the solution for  $T = 1$  is that higher order expectations are the same as first order expectations. This can be seen as follows. Bacchetta and van Wincoop [2004a] show that higher order expectations are equal to first order expectations plus average expectations of future market expecta-

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<sup>22</sup>In Bacchetta and van Wincoop [2003] we solve the model for the case where investors have infinite horizons. The solution is then complicated by the fact that investors also need to hedge against changes in expected future returns. This hedge term depends on the infinite state space, which is truncated to obtain an approximate solution. Numerical results are almost identical to the case of overlapping generations.

tional errors. For example, the second order expectation of  $f_{t+2}$  can be written as  $\overline{E}_t^2 f_{t+2} = \overline{E}_t f_{t+2} + \overline{E}_t(\overline{E}_{t+1} f_{t+2} - f_{t+2})$ . When  $T = 1$  investors do not expect the market to make expectational errors next period. An investor may believe at time  $t$  that he has different private information about  $f_{t+1}$  than others. However, that information is no longer relevant next period since  $f_{t+1}$  is observed at  $t + 1$ .<sup>23</sup>

While not critical, we make the further simplifying assumptions in this section that  $b_t$  and  $f_t$  are i.i.d., i.e.,  $\rho_b = 0$  and  $f_t = \varepsilon_t^f$ . Replacing higher order with first order expectations, equation (7) then becomes:

$$s_t = \frac{1}{1 + \alpha} \left[ f_t + \frac{\alpha}{1 + \alpha} \overline{E}_t f_{t+1} \right] - \frac{\alpha}{1 + \alpha} \gamma \sigma^2 b_t \quad (12)$$

Only the average expectation of  $f_{t+1}$  appears. We have replaced  $\sigma_t^2$  with  $\sigma^2$  since we will focus on the stochastic steady state where second order moments are time-invariant.

### III.A Solving the Model with Heterogenous Information

When  $T = 1$  investors receive private signals  $v_t^i$  about  $f_{t+1}$ , as in (9). Therefore the average expectation  $\overline{E}_t f_{t+1}$  in (12) depends on the average of private signals, which is equal to  $f_{t+1}$  itself. This implies that the exchange rate  $s_t$  depends on  $f_{t+1}$ , so that the exchange rate becomes itself a source of information about  $f_{t+1}$ . However, the exchange rate is not fully revealing as it also depends on unobserved aggregate hedge trades  $b_t$ . To determine the information signal about  $f_{t+1}$  provided by the exchange rate we need to know the equilibrium exchange rate equation. We conjecture that

$$s_t = \frac{1}{1 + \alpha} f_t + \lambda_f f_{t+1} + \lambda_b b_t \quad (13)$$

Since an investor observes  $f_t$ , the signal he gets from the exchange rate can be written

$$\frac{\tilde{s}_t}{\lambda_f} = f_{t+1} + \frac{\lambda_b}{\lambda_f} b_t \quad (14)$$

where  $\tilde{s}_t = s_t - \frac{1}{1 + \alpha} f_t$  is the "adjusted" exchange rate. The variance of the error of this signal is  $(\lambda_b / \lambda_f)^2 \sigma_b^2$ . Consequently, investor  $i$  infers  $E_t^i f_{t+1}$  from three sources of information: i) the distribution of  $f_{t+1}$ ; ii) the signal  $v_t^i$ ; iii) the adjusted exchange

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<sup>23</sup>See Bacchetta and van Wincoop [2004a] for a more detailed discussion of this point.

rate (i.e., (14)). Since errors in each of these signals have a normal distribution, the projection theorem implies that  $E_t^i f_{t+1}$  is given by a weighted average of the three signals, with the weights determined by the precision of each signal. We have:

$$E_t^i f_{t+1} = \frac{\beta^v v_t^i + \beta^s \tilde{s}_t / \lambda_f}{D} \quad (15)$$

where  $\beta^v = 1/\sigma_v^2$ ,  $\beta^s = 1/(\lambda_b/\lambda_f)^2 \sigma_b^2$ ,  $\beta^f = 1/\sigma_f^2$ , and  $D = 1/\text{var}(f_{t+1}) = \beta^v + \beta^f + \beta^s$ . For the exchange rate signal, the precision is complex and depends both on  $\sigma_b^2$  and  $\lambda_b/\lambda_f$ , the latter being endogenous. By substituting (15) into (12) and using the fact that  $\int_0^1 v_t^i di = f_{t+1}$  in computing  $\bar{E}_t f_{t+1}$ , we get:

$$s_t = \frac{1}{1+\alpha} f_t + z \frac{\alpha}{(1+\alpha)^2} \frac{\beta^v}{D} f_{t+1} - z \frac{\alpha}{1+\alpha} \gamma \sigma^2 b_t \quad (16)$$

where  $z = 1/(1 - \frac{\alpha}{(1+\alpha)^2} \frac{\beta^s}{\lambda_f D}) > 1$ . Equation (16) confirms the conjecture (13). Equating the coefficients on  $f_{t+1}$  and  $b_t$  in (16) to respectively  $\lambda_f$  and  $\lambda_b$  yields implicit solutions to these parameters.

We will call  $z$  the *magnification factor*: the equilibrium coefficient of  $b_t$  in (16) is the direct effect of  $b_t$  in (12) multiplied by  $z$ . This magnification can be explained by rational confusion. When the exchange rate changes, investors do not know whether this is driven by hedge trades or by information about future macroeconomic fundamentals by other investors. Therefore, they always revise their expectations of fundamentals when the exchange rate changes (equation (15)). This rational confusion magnifies the impact of the unobserved hedge trades on the exchange rate. More specifically, from (12) and (15), we can see that a change in  $b_t$  has two effects on  $s_t$ . First, it affects  $s_t$  directly in (12) through the risk-premium channel. Second, this direct effect is magnified by an increase in  $\bar{E}_t f_{t+1}$  from (15).

The magnification factor can be written as<sup>24</sup>

$$z = 1 + \frac{\beta^s}{\beta^v} \quad (17)$$

The magnification factor therefore depends on the precision of the exchange rate signal relative to the precision of the private signal. The better the quality of the exchange rate signal, the more weight is given to the exchange rate in forming

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<sup>24</sup>Substitute  $\lambda_f = z \frac{\alpha}{(1+\alpha)^2} \frac{\beta^v}{D}$  into  $z = 1/(1 - \frac{\alpha}{(1+\alpha)^2} \frac{\beta^s}{\lambda_f D})$  and solve for  $z$ .

expectations of  $f_{t+1}$ , and therefore the larger the magnification of the unobserved hedge trades.

Figure 1 shows the impact of two key parameters on magnification. A rise in the private signal variance  $\sigma_v^2$  at first raises magnification and then lowers it. Two opposite forces are at work. First, an increase in  $\sigma_v^2$  reduces the precision  $\beta^v$  of the private signal. Investors therefore give more weight to the exchange rate signal, which enhances the magnification factor. Second, a rise in  $\sigma_v^2$  implies less information about next period's fundamental and therefore a lower weight of  $f_{t+1}$  in the exchange rate. This reduces the precision  $\beta^s$  of the exchange rate signal, which reduces the magnification factor. For large enough  $\sigma_v^2$  this second factor dominates. The magnification factor is therefore largest for intermediate values of the quality of private signals. Figure 1 also shows that a higher variance  $\sigma_b^2$  of hedging shocks always reduces magnification. It reduces the precision  $\beta^s$  of the exchange rate signal.

### III.B Disconnect from Observed Fundamentals

In order to precisely identify the channels through which information heterogeneity disconnects the exchange rate from observed fundamentals, we now compare the model to a benchmark with identically informed investors. The benchmark we consider is the case where investors receive the same signal on future  $f_t$ 's, i.e., they have incomplete but common knowledge on future fundamentals. With common knowledge all investors receive the signal

$$v_t = f_{t+T} + \varepsilon_t^v \quad \varepsilon_t^v \sim N(0, \sigma_{v,c}^2) \quad (18)$$

where  $\varepsilon_t^v$  is independent of  $f_{t+T}$ .

Defining the precision of this signal as  $\beta^{v,c} \equiv 1/\sigma_{v,c}^2$ , the conditional expectation of  $f_{t+1}$  is

$$E_t^i f_{t+1} = \bar{E}_t f_{t+1} = \frac{\beta^{v,c} v_t}{d} \quad (19)$$

where  $d \equiv 1/\text{var}_t(f_{t+1}) = \beta^{v,c} + \beta^f$ . Substitution into (12) yields the equilibrium exchange rate:

$$s_t = \frac{1}{1+\alpha} f_t + \lambda_v v_t + \lambda_b^c b_t \quad (20)$$

where  $\lambda_v = \frac{\alpha}{(1+\alpha)^2} \beta^{v,c}/d$ , and  $\lambda_b^c = -\frac{\alpha}{1+\alpha} \gamma \sigma_c^2$ . Here  $\sigma_c^2$  is the conditional variance of next period's exchange rate in the common knowledge model. In this case the



exchange rate is fully revealing, since by observing  $s_t$  investors can perfectly deduce  $b_t$ . Thus,  $\lambda_b^c$  is equal to the direct risk-premium effect of  $b_t$  given in (12).

We can now compare the connection between the exchange rate and observed fundamentals in the two models. In the heterogeneous information model the observed fundamental is  $f_t$ , while in the common knowledge model it also includes  $v_t$ . We compare the  $R^2$  of a regression of the exchange rate on observed fundamentals in the two models. From (13), the  $R^2$  in the heterogeneous information model is defined by:

$$\frac{R^2}{1 - R^2} = \frac{\frac{1}{(1+\alpha)^2} \sigma_f^2}{\lambda_f^2 \sigma_f^2 + z^2 \left(\frac{\alpha}{1+\alpha}\right)^2 \gamma^2 \sigma^4 \sigma_b^2} \quad (21)$$

From (20) the  $R^2$  in the common knowledge model is defined by:

$$\frac{R^2}{1 - R^2} = \frac{\frac{1}{(1+\alpha)^2} \sigma_f^2 + \lambda_v^2 (\sigma_f^2 + \sigma_{v,c}^2)}{\left(\frac{\alpha}{1+\alpha}\right)^2 \gamma^2 \sigma_c^4 \sigma_b^2} \quad (22)$$

If the conditional variance of the exchange rate is the same in both models the  $R^2$  is clearly lower in the heterogeneous information model. Two factors contribute to this. First, the contribution of unobserved trades to exchange rate volatility is amplified, as measured by the magnification factor  $z$  in the denominator of (21). Second, the average signal in the heterogeneous information model, which is equal to the future fundamental, is unobserved and therefore contributes to reducing the  $R^2$ . It also appears in the denominator of (21). In contrast, the signal about future fundamentals is observed in the common knowledge model, and therefore contributes to raising the  $R^2$ . The variance of this signal,  $\sigma_f^2 + \sigma_{v,c}^2$ , appears in the numerator of (22). The conditional variance of the exchange rate also contributes to the  $R^2$ . It can be higher in either model, dependent on assumptions about parameter values and quality of the public and private signals.

### III.C Order Flow

Evans and Lyons [2002a] define order flow as “the net of buyer-initiated and seller-initiated orders.” While each transaction involves a buyer and a seller, the sign of the transaction is determined by the initiator of the transaction. The initiator of a transaction is the trader (either buyer or seller) who acts based on new private information. Here private information is broadly defined. In our setup it includes

both private information about the future fundamental and private information that leads to hedge trades. The passive side of trade varies across models. In a quote-driven dealer market, such as modeled by Evans and Lyons [2002a], the quoting dealer is on the passive side. The foreign exchange market has traditionally been characterized as a quote-driven multi-dealer market, but the recent increase in electronic trading (e.g., EBS) implies that a majority of trade is done through an auction market. In that case the limit orders are the passive side of transactions and provide liquidity to the market. The initiated orders are referred to as market orders that are confronted with the passive outstanding limit order book.

In our modeling of order flow we think of the foreign exchange market as an auction market. We split the demand  $b_{F,t}^i$  by investor  $i$  into order flow (market orders) and limit orders. Limit orders are associated with the component of demand that depends on the price (exchange rate) and common information. These are passive orders that are only executed when confronted with market orders. Market orders are associated with the component of demand that depends on private information.<sup>25</sup>

Using (4), (13) and (15), we can write total demand by individual  $i$  as

$$b_{F,t}^i = \frac{1 + \alpha}{\alpha\gamma\sigma^2z} \left( \frac{1}{1 + \alpha} f_t - s_t \right) + \frac{\beta^v}{(1 + \alpha)\gamma\sigma^2D} v_t^i - b_t^i \quad (23)$$

Limit orders are captured by the first term, while order flow is captured by the sum of the last two terms. If there were no private information, so that the last two terms are equal to their unconditional mean of zero, demand would be the same for all investors. Since aggregate supply is zero, the holdings of each investor would always be zero. In that case the exchange rate may change due to new

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<sup>25</sup>One way to formalize this separation into limit and market orders is to introduce foreign exchange dealers to whom investors delegate price discovery. Dealers are simply a veil, passing on customer orders to the interdealer market, where price discovery takes place. Customers submit their demand functions to dealers through a combination of limit and market orders. Dealers can place both types of orders in the interdealer electronic auction market, but need to place the limit orders before customer orders are known. If we introduce an infinitesimal trading cost in the interdealer market that is proportional to the volume of executed trades, dealers will submit limit orders that are equal to the expected customer orders based on public information. The unexpected customer orders are associated with private information and are submitted as market orders to the interdealer market. This formalization also connects well to the existing data, which is for interdealer order flow.

public information ( $s_t = f_t/(1 + \alpha)$ ), but this happens without any transactions in the foreign exchange market.

In the presence of private information there is trade in the foreign exchange market. We define  $\Delta x_t^i$  as order flow of investor  $i$ , the sum of the last two terms on the right hand side of (23).<sup>26</sup> Aggregate order flow  $\Delta x_t = \int_0^1 \Delta x_t^i di$  is then equal to

$$\Delta x_t = \frac{\beta^v}{(1 + \alpha)\gamma\sigma^2 D} f_{t+1} - b_t \quad (24)$$

Taking the aggregate of (23), imposing market equilibrium, we get

$$s_t = \frac{1}{1 + \alpha} f_t + z \frac{\alpha}{1 + \alpha} \gamma\sigma^2 \Delta x_t \quad (25)$$

Equation (25) shows that the exchange rate is related in a simple way to a commonly observed fundamental and order flow. The order flow term captures the extent to which the exchange rate changes due to the aggregation of private information. The impact of order flow is larger the bigger the magnification factor  $z$ . A higher level of  $z$  implies that the order flow is more informative about the future fundamental.

It is easily verified that in the common knowledge model

$$s_t = \frac{1}{1 + \alpha} f_t + \lambda_v v_t + \frac{\alpha}{1 + \alpha} \gamma\sigma^2 \Delta x_t \quad (26)$$

In that case order flow is only driven by hedge trades. Since these trades have no information content about future fundamentals, the impact of order flow on the exchange rate is smaller (not multiplied by the magnification factor  $z$ ). A comparison between (25) and (26) clearly shows that the exchange rate is more closely connected to order flow in the heterogeneous information model and more closely connected to public information in the common knowledge model.

Equations (25) and (26) are different from the specification used in empirical analysis, where the exchange rate is usually in first differences. The reason is that in this section  $s_t$  is stationary, while in the data it is non-stationary. If we assume that  $f_t$  follows a random walk in the above example, we obtain an equation that is

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<sup>26</sup>More generally, when the fundamentals are not i.i.d., the expectations of  $v_t^i$  and  $b_t^i$  based on public information are non-zero. For example, when  $f$  follows a random walk the expectation of  $v_t^i$  based on public information is  $f_t$ . In that case order flow is defined as the linear combination of  $v_t^i$  and  $b_t^i$  in the demand  $b_{F,t}^i$  that is orthogonal to public information.

close to the one used in empirical analyses.<sup>27</sup> In the numerical analysis of Section V,  $s_t$  is non-stationary and we run regressions in differences.

A related point is that when the fundamental  $f$  is non-stationary, order flow associated with private information about future fundamentals has a permanent impact on the exchange rate. It is not the case though that *cumulative* order flow and the exchange rate are cointegrated. Hedge trades have a transitory impact on the exchange rate, but a permanent effect on cumulative order flow. This point is made more precise in Appendix D for the case where  $f$  follows a random walk.<sup>28</sup>

## IV Model Implications: Dynamics

In this section, we examine the more complex dynamic properties of the model when  $T > 1$ . There are two important implications. First, it creates endogenous persistence of the impact of non-observable shocks on the exchange rate. Second, higher order expectations differ from first order expectations when  $T > 1$ . Even for  $T = 2$  expectations of infinite order affect the exchange rate. We show that higher order expectations tend to increase the magnification effect, but have an ambiguous impact on the disconnect. We now examine these two aspects in turn.

### IV.A Persistence

When  $T > 1$ , even transitory non-observable shocks have a persistent effect on the exchange rate. This is caused by the combination of heterogeneous information and the positive weight given to information from previous periods in forming expectations. The exchange rate at time  $t$  depends on future fundamentals  $f_{t+1}$ ,  $f_{t+2}$ , ...,  $f_{t+T}$ , and therefore provides information about each of these future fundamentals. A transitory unobservable shock to  $b_t$  affects the exchange rate at time  $t$  and

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<sup>27</sup>More precisely, in this case we would find  $\Delta s_t = (1 - \lambda_f)\Delta f_t + z\frac{\alpha}{1+\alpha}\gamma\sigma_t^2\Delta x_t - \lambda_b\varepsilon_{t-1}^b$ . When both  $b$  and  $f$  follow random walks we obtain an equation for the common knowledge model very similar to that implied by the model of Evans and Lyons [2002a]:  $\Delta s_t = \Delta f_t + \alpha\gamma\sigma_t^2\Delta x_t$ . Their model is indeed one where both “portfolio shifts”  $\Delta b_t$  and changes in observed fundamentals  $\Delta f_t$  are permanent and agents do not have private information about future fundamentals.

<sup>28</sup>It also holds in this section, where  $f$  is stationary. In that case the exchange rate is stationary, but cumulative order flow is non-stationary since transitory hedge trades have a permanent effect on cumulative order flow.

therefore affects the expectations of all future fundamentals up to time  $t+T$ . This rational confusion will last for  $T$  periods, until the final one of these fundamentals,  $f_{t+T}$ , is observed. Until that time investors will continue to give weight to  $s_t$  in forming their expectations of future fundamentals, so that  $b_t$  continues to affect the exchange rate.<sup>29</sup> As investors gradually learn more about  $f_{t+1}, f_{t+2}, \dots, f_{t+T}$ , both by observing them and through new signals, the impact on the exchange rate of the shock to  $b_t$  gradually dissipates.

The persistence of the impact of  $b$ -shocks on the exchange rate is also affected by the persistence of the shock itself. When the  $b$ -shock itself becomes more persistent, it is more difficult for investors to learn about fundamentals up to time  $t+T$  from exchange rates subsequent to time  $t$ . The rational confusion is therefore more persistent and so is the impact of  $b$ -shocks on the exchange rate.

## IV.B Higher Order Expectations

The topic of higher order expectations is a difficult one, but it has potentially important implications for asset pricing. Since a detailed analysis falls outside the scope of this paper, we limit ourselves to a brief discussion regarding the impact of higher order expectations on the connection between the exchange rate and observed fundamentals. We apply the results of Bacchetta and van Wincoop [2004a], where we provide a general analysis of the impact of higher order expectations on asset prices.<sup>30</sup> We still assume that  $\rho_b = 0$ .

Let  $\bar{s}_t$  denote the exchange rate that would prevail if the higher order expectations in (7) are replaced by first order expectations.<sup>31</sup> In Bacchetta and van Wincoop [2004a] we show that the present value of the difference between higher and first order expectations depends on average first-order expectational errors about average private signals. In Appendix C we show that in our context this

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<sup>29</sup>This result is related to findings by Brown and Jennings [1989] and Grundy and McNichols [1989], who show in the context of two-period noisy rational expectations models that the asset price in the second period is affected by the asset price in the first period.

<sup>30</sup>Allen, Morris and Shin [2003] also provide an insightful analysis of higher order expectations with an asset price, but they do not consider an infinite horizon model.

<sup>31</sup>That is  $\bar{s}_t = \frac{1}{1+\alpha} \sum_{k=0}^{\infty} \left(\frac{\alpha}{1+\alpha}\right)^k \bar{E}_t (f_{t+k} - \alpha\gamma\sigma_{t+k}^2 b_{t+k})$

leads to

$$s_t = \bar{s}_t + \frac{1}{1 + \alpha} \sum_{k=2}^T \pi_k (\bar{E}_t f_{t+k} - f_{t+k}) \quad (27)$$

The parameters  $\pi_k$  are defined in the Appendix and are positive in all numerical applications. Higher order expectations therefore introduce a new asset price component, which depends on average first-order expectational errors about future fundamentals.

Moreover, the expectational errors  $\bar{E}_t f_{t+k} - f_{t+k}$  depend on errors in public signals; based on private information alone these average expectational errors would be zero. There are two types of errors in public signals. First, there are errors in the exchange rate signals that are caused by the unobserved hedge trades at time  $t$  and earlier. This implies that unobserved hedge trades receive a larger weight in the equilibrium exchange rate. The other type of errors in public signals are errors in the signals based on the process of  $f_t$ . These errors depend negatively on future innovations in the fundamental, which implies that the exchange rate depends less on unobserved future fundamentals. To summarize, hedge shocks are further magnified by the presence of higher order expectations, while the overall impact on the connection between the exchange rate and observed fundamentals is ambiguous.<sup>32</sup>

## V Model Implications: Numerical Analysis

We now solve the model numerically to illustrate the various implications of the model discussed above. We first consider a benchmark parameterization and then discuss the sensitivity of the results to changing some key parameters.

### V.A A Benchmark Parameterization

The parameters of the benchmark case are reported in Table 1. They are chosen mainly to illustrate the potential impact of information dispersion; they are not calibrated or chosen to match any data moments. We assume that the observable

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<sup>32</sup>In Bacchetta and van Wincoop [2004a], we show that the main impact of higher order expectations is to disconnect the price from the present value of future observable fundamentals.

fundamental  $f$  follows a random walk, whose innovations have a standard deviation of  $\sigma_f = 0.01$ . We assume that the extent of private information is small by setting a high standard deviation of the private signal error of  $\sigma_v = 0.08$ . The unobservable fundamental  $b$  follows an AR process with autoregressive coefficient of  $\rho_b = 0.8$  and a standard deviation  $\sigma_b = 0.01$  of innovations. Although we have made assumptions about both  $\sigma_b$  and risk-aversion  $\gamma$ , they enter multiplicatively in the model, so only their product matters. Finally, we assume  $T = 8$ , so that agents obtain private signals about fundamentals eight periods before they are realized.

Figure 2 shows some of the key results from the benchmark parameterization. Panels A and B show the dynamic impact on the exchange rate in response to one-standard deviation shocks in the private and common knowledge models. In the heterogeneous agent model, there are two shocks: a shock  $\varepsilon_{t+T}^f$  ( $f$ -shock), which first affects the exchange rate at time  $t$ , and a shock  $\varepsilon_t^b$  ( $b$ -shock). In the common knowledge model there are also shocks  $\varepsilon_t^v$ , which affect the exchange rate through the commonly observable fundamental  $v_t$ . In order to facilitate comparison, we set the precision of the public signal such that the conditional variance of next period's exchange rate is the same as in the heterogeneous information model. This implies that the unobservable hedge trades have the same risk-premium effect in the two models. We will show below that our key results do not depend on the assumed precision of the public signal.

### Magnification

The magnification factor in the benchmark parameterization turns out to be substantial: 7.2. This is visualized in Figure 2 by comparing the instantaneous response of the exchange rate to the  $b$ -shocks in the two models in panels A and B. The only reason the impact of a  $b$ -shock is so much bigger in the heterogeneous information model is the magnification factor associated with information dispersion.

### Persistence

We can see from panel A that after the initial shock the impact of the  $b$ -shocks dies down almost as a linear function of time. The half-life of the impact of the shock is 3 periods. After 8 periods the rational confusion is resolved and the impact is the same as in the public information model, which is close to zero.

The meaning of a 3-period half-life depends of course on what we mean by a period in the model. What is critical is not the length of a period, but the length of time it takes for uncertainty about future macro variables to be resolved. For example, assume that  $T$  is eight months. If a period in our model is a month, then  $T = 8$ . If a period is three days, then  $T = 80$ . We find that the half-life of the impact of the unobservable hedge shocks on the exchange rate that can be generated by the model remains virtually unchanged as we change the length of a period. For  $T = 8$  the half life is about 3, while for  $T = 80$  it is about 30.<sup>33</sup> In both cases the half-life is 3 months. Persistence is therefore driven critically by the length of time it takes for uncertainty to resolve itself. Deviations of the exchange rate from observed fundamentals can therefore be very long-lasting when it takes a long time before expectations about future fundamentals can be validated, such as expectations about the long-term technology growth rate of the economy.

### **Exchange rate disconnect in the short and the long run**

Panel C reports the contribution of unobserved hedge trades to the variance of  $s_{t+k} - s_t$  at different horizons. In the heterogeneous information model, 70% of the variance of a 1-period change in the exchange rate is driven by the unobservable hedge trades, while in the common knowledge model it is a negligible 1.3%. While in the short-run unobservable fundamentals dominate exchange rate volatility, in the long-run observable fundamentals dominate. For example, the contribution of hedge trades to the variance of exchange rate changes over a 10-period interval is less than 20%. As seen in panel A, the impact of hedge trades on the exchange rate gradually dies down as rational confusion dissipates over time.

In order to determine the relationship between exchange rates and observed fundamentals, panel D reports the  $R^2$  of a regression of  $s_{t+k} - s_t$  on all current and lagged *observed* fundamentals. In the heterogeneous information model this includes all one period changes in the fundamental  $f$  that are known at time

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<sup>33</sup>When we change the length of a period we also need to change other model parameters, such as the standard deviations of the shocks. In doing so we restrict parameters such that (i) the contribution of  $b$ -shocks to  $\text{var}(s_{t+1} - s_t)$  is the same as in the benchmark parameterization and (ii) the impact of  $b$ -shocks on exchange rate volatility remains largely driven by information dispersion (large magnification factor). For example, when we change the benchmark parameterization such that  $T = 80$ ,  $\sigma_v = 0.26$ ,  $\sigma_f = 0.0016$  and  $\alpha = 44$ , the half-life is 28 periods. The magnification factor is 48.



$t + k$ :  $f_{t+s} - f_{t+s-1}$ , for  $s \leq k$ . In the common knowledge model it also includes the corresponding one-period changes in the public signal  $v$ . The  $R^2$  is close to 1 for all horizons in the common knowledge model, while it is much lower in the heterogeneous information model. At the one-period horizon it is only 0.14; it then rises as the horizon increases, to 0.8 for a 20-period horizon. This is consistent with extensive findings that macroeconomic fundamentals have weak explanatory power for exchange rates in the short to medium run, starting with Meese and Rogoff [1983], and findings of a closer relationship over longer horizons.<sup>34</sup>

Two factors account for the results in panel D. The first is that the relative contribution of unobservable hedge shocks to exchange rate volatility is large in the short-run and small in the long-run, as illustrated in panel C. The second factor is that through private signals the exchange rate at time  $t$  is also affected by innovations  $\varepsilon_{t+1}^f, \dots, \varepsilon_{t+T}^f$  in future fundamentals that are not yet observed today. In the long-run these become observable, again contributing to a closer relationship between the exchange rate and observed fundamentals in the long-run.

### Exchange rate and future fundamentals

Recently Engel and West [2002] and Froot and Ramadorai [2002] have reported evidence that exchange rate changes predict future fundamentals, but only weakly so. Our model is consistent with these findings. Panel E of Figure 2 reports the  $R^2$  of a regression  $f_{t+k} - f_{t+1}$  on  $s_{t+1} - s_t$  for  $k \geq 2$ . The  $R^2$  is positive, but is never above 0.14. The exchange rate is affected by the private signals of future fundamentals, which aggregate to the future fundamentals. However, most of the short-run volatility of exchange rates is associated with unobservable hedge trades, which do not predict future fundamentals.

### Exchange rate and order flow

Order flow is again defined as the component of demand for foreign bonds that is orthogonal to public information (other than the yet to be determined  $s_t$ ). Details of how it is computed are discussed in Appendix D. With  $x_t$  defined as cumulative order flow, panel F reports the  $R^2$  of a regression of  $s_{t+k} - s_t$  on  $x_{t+k} - x_t$ . The  $R^2$  is large and rises with the horizon from 0.84 for  $k = 1$  to

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<sup>34</sup>See MacDonald and Taylor [1993], Mark [1995], Chinn and Meese [1995], Mark and Sul [2001], Froot and Ramadorai [2002] and Gourinchas and Rey [2004].

0.97 for  $k = 40$ . Although it appears that the  $R^2$  approaches 1 as  $k$  approaches infinity, it asymptotically reaches a level near 0.99.<sup>35</sup> We show in the Appendix that cumulative order flow and the exchange rate are not cointegrated. Both the exchange rate and cumulative order flow depend on  $f_t$ . However, cumulative order flow also depends on the infinite sum of all past hedge demand innovations, while the coefficient on past hedge innovations in the equilibrium exchange rate approaches zero for long lags.

It is important to point out that the close relationship between the exchange rate and order flow in the long run is not inconsistent with the close relationship between the exchange rate and observed fundamentals in the long run. When the exchange rate rises due to private information about permanently higher future fundamentals, the information reaches the market through order flow. Eventually the future fundamentals will be observed, so that there is a link between the exchange rate and the observed fundamentals. But most of the information about higher future fundamentals is aggregated into the price through order flow. Order flow associated with information about future fundamentals has a permanent effect on the exchange rate.

Our results can be compared to similar regressions that have been conducted based on the data. Evans and Lyons [2002a] estimate regressions of one-day exchange rate changes on daily order flow. They find an  $R^2$  of 0.63 and 0.40 for respectively the DM/\$ and the yen/\$ exchange rate, based on four months of daily data in 1996. Evans and Lyons [2002b] report results for nine currencies. They point out that exchange rate changes for any currency pair can also be affected by order flow for other currency pairs. Regressing exchange rate changes on order flow for all currency pairs they find an average  $R^2$  of 0.67 for their nine currencies. The pictures for the exchange rate and cumulative order flow reported in Evans and Lyons [2002a] suggest that the link is even stronger over horizons longer than one day, although their dataset is too short to formally run such regressions.

The strong link between order flow and exchange rates in both the model and the data implies that most information reaches the market through order flow, and is therefore private information rather than public information. While

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<sup>35</sup>The relationship between  $s_{t+k} - s_t$  and  $x_{t+k} - x_t$  does not always get stronger for longer horizons. For low values of  $T$  the  $R^2$  declines with  $k$  and then converges asymptotically to a positive level.

not reported in panel F, the  $R^2$  of regressions of exchange rate changes on order flow in the public information model is close to zero. Two factors contribute to the much closer link between order flow and exchange rates in the heterogeneous information model. First, in the heterogeneous information model both private information about future fundamentals and hedge trades contribute to order flow, while in the public information model only hedge trades contribute to order flow. Second, the impact on the exchange rate of the order flow due to hedge trades is much larger in the heterogeneous information model. The reason is that order flow is informative about future fundamentals in the heterogeneous information model. As illustrated in section III.C, the magnification factor  $z$  applied to the impact of  $b$ -shocks on the exchange rate also applies to the impact of order flow on the exchange rate.

Figure 3 reports simulations of the exchange rate and cumulative order flow over 40 periods. The Figure shows four simulations, based on different random draws of the observable and unobservable fundamentals.<sup>36</sup> The simulations confirm a close link between the exchange rate and cumulative order flow at both short and long horizons. Some of these pictures look quite similar to those reported by Evans and Lyons [2002a] for the DM/\$ and yen/\$.

## V.B Sensitivity to Model Parameters

In this subsection, we consider the parameter sensitivity of two key moments: the  $R^2$  of a regression of  $s_{t+1} - s_t$  on observed fundamentals at  $t + 1$  and earlier and the  $R^2$  of a regression of  $s_{t+1} - s_t$  on order flow  $x_{t+1} - x_t$ . These are the moments reported for  $k = 1$  in panels D and F of Figure 2.

A first issue is that the precision of the public signal in the common knowledge model does not play an important role in the comparison with the heterogeneous information model. In particular, it has little influence on the stark difference between the two models regarding the connection between the exchange rate and observed fundamentals. Consider the  $R^2$  of a regression of a one-period change in the exchange rate on all current and past observed fundamentals, as reported in Figure 2D. In the heterogeneous information model it is 0.14, while in the public

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<sup>36</sup>Both the log of the exchange rate and cumulative order flow are set at zero at the start of the simulation.

information model it varies from 0.97 to 0.99 as we change the variance of the noise in the public signal from infinity to zero.<sup>37</sup>

We now consider sensitivity analysis to four key model parameters in the heterogeneous information model:  $\sigma_v$ ,  $\sigma_b$ ,  $\rho_b$  and  $T$ . The results are reported in Figure 4. Not surprisingly, the two  $R^2$ 's are almost inversely related as we vary parameters. The larger the impact of order flow as a channel through which information is transmitted to the market, the smaller is the explanatory power of commonly observed macro fundamentals.<sup>38</sup>

An increase in  $\sigma_v$ , implying less precise private information, reduces the link between the exchange rate and order flow and increases the link between the exchange rate and observed fundamentals. In the limit as the noise in private signals approaches infinity, the heterogeneous information model approaches the public information model (with uninformative signals).

Somewhat surprisingly, an increase in the noise originating from hedge trades, by either raising the standard deviation  $\sigma_b$  or the persistence  $\rho_b$ , tends to strengthen the link between the exchange rate and observed fundamentals and reduce the link between the exchange rate and order flow. However, the effect is relatively small due to offsetting factors. Order flow becomes less informative about future fundamentals with more noisy hedge trades. This reduces the impact of order flow on the exchange rate. On the other hand, the volatility of order flow increases, which contributes positively to the  $R^2$  for order flow. The former effect slightly dominates.

It is also worthwhile pointing out that the assumed stationarity of hedge trades in the benchmark parameterization is not responsible for the much weaker relationship between the exchange rate and observed fundamentals in the short-run than the long-run. Even if we assume  $\rho_b = 1$ , so that unobserved aggregate hedge trades follow a random walk as well, this finding remains largely unaltered. The

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<sup>37</sup>In Figure 2, we have assumed that the precision of the public signal is such that the conditional variance of the exchange rate is the same in the two models. This implies a standard deviation of the error in the public signal of 0.033.

<sup>38</sup>The two lines do not add to one. The reason is that some variables that are common knowledge are not included in the regression on observed fundamentals. These are past exchange rates and hedge demand  $T$  periods ago. Past exchange rates are not included since they are not traditional fundamentals. Hedge demand  $T$  periods ago can be indirectly derived from exchange rates  $T$  periods ago and earlier, but is not a directly observable fundamental.

$R^2$  for observed fundamentals rises from 0.21 for a 1-period horizon to 0.85 for a 40-period horizon.

The final panel of Figure 4 shows the impact of changing  $T$ . Initially, an increase in  $T$  leads to a closer link between order flow and the exchange rate and a weaker link between observed fundamentals and the exchange rate. The reason is that as  $T$  increases the quality of private information improves because agents have signals about fundamentals further into the future. This implies that the impact of order flow on the exchange rate increases. Moreover, order flow itself also becomes more volatile as more private information is aggregated. However, beyond a certain level of  $T$ , the link between the exchange rate and order flow is weakened when  $T$  is raised further. The reason is that the improved quality of information reduces the conditional variance  $\sigma^2$  of next period's exchange rate. This reduces the effect of order flow on the exchange rate, as can be seen from (25).

## VI Conclusion

The close relationship between order flow and exchange rates, as well as the large volume of trade in the foreign exchange market, suggest that investor heterogeneity is key to understanding exchange rate dynamics. In this paper we have explored the implications of information dispersion in a simple model of exchange rate determination. We have shown that these implications are rich and that investors' heterogeneity can be an important element in explaining the behavior of exchange rates. In particular, the model can account for some important stylized facts on the relationship between exchange rates, fundamentals and order flow: (i) fundamentals have little explanatory power for short to medium run exchange rate movements, (ii) over long horizons the exchange rate is closely related to observed fundamentals, (iii) exchange rate changes are a weak predictor of future fundamentals, and (iv) the exchange rate is closely related to order flow.

The paper should be considered only as a first step in a promising line of research. A natural next step is to confront the model to the data. While the extent of information dispersion and unobservable hedge trades are not known, they both affect order flow. Some limited data on order flow are now available and will help tie down the key model parameters. The magnification factor may

be quite large. Back-of-the-envelope calculations by Gennotte and Leland [1990] in the context of a static model for the U.S. stock market crash of October 1987 suggest that the impact of a \$6 billion unobserved supply shock was magnified by a factor 250 due to rational confusion about the source of the stock price decline. In the context of foreign exchange markets, Osler [2003] presents evidence that trades which are uninformative about future fundamentals can have a very large impact on the price.

There are several directions in which the model can be extended. The first is to explicitly model nominal rigidities as in the “new open economy macro” literature. In that literature exchange rates are entirely driven by commonly observed macro fundamentals. Conclusions that have been drawn about optimal monetary and exchange rate policies are likely to be substantially revised when introducing investor heterogeneity. Another direction is to consider alternative information structures. For example, the information received by agents may differ in its quality or in its timing. There can also be heterogeneity about the knowledge of the underlying model. For example, in Bacchetta and van Wincoop [2004b], we show that if investors receive private signals about the persistence of shocks, the impact of observed variables on the exchange rate varies over time. The rapidly growing body of empirical work on order flow in the foreign exchange microstructure literature is likely to increase our understanding of the nature of the information structure, providing guidance to future modeling.

# Appendix

## A Derivation of equation (7)

It follows from (1), (2), (3), and (6) that

$$s_t = \frac{1}{1+\alpha} f_t - \frac{\alpha}{1+\alpha} \gamma \sigma_t^2 b_t + \frac{\alpha}{1+\alpha} \bar{E}_t^1(s_{t+1}) \quad (28)$$

Therefore

$$\bar{E}_t^1(s_{t+1}) = \frac{1}{1+\alpha} \bar{E}_t^1(f_{t+1}) - \frac{\alpha}{1+\alpha} \gamma \sigma_{t+1}^2 \bar{E}_t^1(b_{t+1}) + \frac{\alpha}{1+\alpha} \bar{E}_t^2(s_{t+2}) \quad (29)$$

Substitution into (28) yields

$$s_t = \frac{1}{1+\alpha} \left[ f_t - \gamma \sigma_t^2 b_t + \frac{\alpha}{1+\alpha} \bar{E}_t^1 \left( f_{t+1} - \gamma \sigma_{t+1}^2 b_{t+1} \right) \right] + \left( \frac{\alpha}{1+\alpha} \right)^2 \bar{E}_t^2(s_{t+2}) \quad (30)$$

Continuing to solve for  $s_t$  this way by forward induction and assuming a no-bubble solution yields (7).

## B Solution method with two-period overlapping investors

The solution method is related to Townsend (1983, section VIII). We start with the conjectured equation (11) for  $s_t$  and check whether it is consistent with the model, in particular with equation (6). For this, we need to estimate the conditional moments of  $s_{t+1}$  and express them as a function of the model's innovations. Finally we equate the parameters from the resulting equation to the initially conjectured equation.

### B.1 The exchange rate equation

From (1)-(3), and the definition of  $f_t$ , it is easy to see that  $i_t^* - i_t = (f_t - s_t)/\alpha$ . Thus, (6) gives (for a constant  $\sigma_t^2$ ):

$$s_t = \frac{\alpha}{1+\alpha} \bar{E}_t^1(s_{t+1}) + \frac{f_t}{1+\alpha} - \frac{\alpha}{1+\alpha} \gamma b_t \sigma^2 \quad (31)$$

We want to express (31) in terms of current and past innovations. First, we have  $f_t = D(L)\varepsilon_t^f$ , where  $D(L) = d_1 + d_2L + d_3L^2 + \dots$ . Second, using (5) we can write  $b_t = C(L)\varepsilon_t^b$ , where  $C(L) = 1 + \rho_bL + \rho_b^2L^2 + \dots$ . What remains to be computed are  $\bar{E}(s_{t+1})$  and  $\sigma^2$ .

Applying (11) to  $s_{t+1}$ , decomposing  $A(L)$  and  $B(L)$ , we have

$$s_{t+1} = a_1\varepsilon_{t+T+1}^f + b_1\varepsilon_{t+1}^b + \boldsymbol{\theta}'\boldsymbol{\xi}_t + A^*(L)\varepsilon_t^f + B^*(L)\varepsilon_{t-T}^b \quad (32)$$

where  $\boldsymbol{\xi}_t' = (\varepsilon_{t+T}^f, \dots, \varepsilon_{t+1}^f, \varepsilon_t^b, \dots, \varepsilon_{t-T+1}^b)$  represents the vector of unobservable innovations,  $\boldsymbol{\theta}' = (a_2, a_3, \dots, a_{T+1}, b_2, \dots, b_{T+1})$  and  $A^*(L) = a_{T+2} + a_{T+3}L + \dots$  (with a similar definition for  $B^*(L)$ ). Thus, we have (since  $\varepsilon_j^f$  and  $\varepsilon_{j-T}^b$  are known for  $j \leq t$ ):

$$E_t^i(s_{t+1}) = \boldsymbol{\theta}'E_t^i(\boldsymbol{\xi}_t) + A^*(L)\varepsilon_t^f + B^*(L)\varepsilon_{t-T}^b \quad (33)$$

$$\sigma^2 = \text{var}_t(s_{t+1}) = a_1^2\sigma_f^2 + b_1^2\sigma_b^2 + \boldsymbol{\theta}'\text{var}_t(\boldsymbol{\xi}_t)\boldsymbol{\theta} \quad (34)$$

We need to estimate the conditional expectation and variance of the unobservable  $\boldsymbol{\xi}_t$  as a function of past innovations.

## B.2 Conditional moments

We follow the strategy of Townsend (1983, p.556), but use the notation of Hamilton [1994, chapter 13]. First, we subtract the known components from the observables  $s_t$  and  $v_t^i$  and define these new variables as  $s_t^*$  and  $v_t^{i*}$ . Let the vector of these observables be  $\mathbf{Y}_t^i = (s_t^*, s_{t-1}^*, \dots, s_{t-T+1}^*, v_t^{i*}, \dots, v_{t-T+1}^{i*})$ . From (32) and (9), we can write:

$$\mathbf{Y}_t^i = \mathbf{H}'\boldsymbol{\xi}_t + \mathbf{w}_t^i \quad (35)$$

where  $\mathbf{w}_t^i = (0, \dots, 0, \varepsilon_t^{vi}, \dots, \varepsilon_{t-T+1}^{vi})'$  and

$$\mathbf{H}' = \begin{bmatrix} a_1 & a_2 & \dots & a_T & b_1 & b_2 & \dots & b_T \\ 0 & a_1 & \dots & a_{T-1} & 0 & b_1 & \dots & b_{T-1} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & a_1 & 0 & 0 & \dots & b_1 \\ d_1 & d_2 & \dots & d_T & 0 & 0 & \dots & 0 \\ 0 & d_1 & \dots & d_{T-1} & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & d_1 & 0 & 0 & \dots & 0 \end{bmatrix}$$



The unconditional means of  $\boldsymbol{\xi}_t$  and  $\mathbf{w}_t^i$  are zero. Define their unconditional variances as  $\tilde{\mathbf{P}}$  and  $\mathbf{R}$ . Then we have (applying eqs. (17) and (18) in Townsend):

$$E_t^i(\boldsymbol{\xi}_t) = \mathbf{M}\mathbf{Y}_t^i \quad (36)$$

where:

$$\mathbf{M} = \tilde{\mathbf{P}}\mathbf{H} [\mathbf{H}'\tilde{\mathbf{P}}\mathbf{H} + \mathbf{R}]^{-1} \quad (37)$$

Moreover,  $\mathbf{P} \equiv \text{var}_t(\boldsymbol{\xi}_t)$  is given by:

$$\mathbf{P} = \tilde{\mathbf{P}} - \mathbf{M}\mathbf{H}'\tilde{\mathbf{P}} \quad (38)$$

### B.3 Solution

First,  $\sigma^2$  can easily be derived from (34) and (38). Second, substituting (36) and (35) into (33), and averaging over investors, gives the average expectation in terms of innovations:

$$\bar{E}_t(s_{t+1}) = \boldsymbol{\theta}'\mathbf{M}\mathbf{H}'\boldsymbol{\xi}_t + A^*(L)\varepsilon_t^f + B^*(L)\varepsilon_{t-T}^b \quad (39)$$

We can then substitute  $\bar{E}_t(s_{t+1})$  and  $\sigma^2$  into (31) so that we have an expression for  $s_t$  that has the same form as (11). We then need to solve a fixed point problem.

Although  $A(L)$  and  $B(L)$  are infinite lag operators, we only need to solve a finitely dimensional fixed point problem in the set of parameters  $(a_1, a_2, \dots, a_T, b_1, \dots, b_{T+1})$ . This can be seen as follows. First, it is easily verified by equating the parameters of the conjectured and equilibrium exchange rate equation for lags  $T$  and greater that  $b_{T+s+1} = \frac{1+\alpha}{\alpha}b_{T+s} + \gamma\sigma^2\rho_b^{T+s-1}$  and  $a_{T+s+1} = \frac{1+\alpha}{\alpha}a_{T+s} - \frac{1}{\alpha}d_s$  for  $s \geq 1$ . Assuming non-explosive coefficients, the solutions to these difference equations give us the coefficients for lags  $T+1$  and greater:  $b_{T+1} = -\alpha\gamma\sigma^2\rho_b^T/(1+\alpha-\alpha\rho_b)$ ,  $b_{T+s} = (\rho_b)^{s-1}b_{T+1}$  for  $s \geq 2$ ,  $a_{T+1} = (1/\alpha)\sum_{s=1}^{\infty}(\alpha/(1+\alpha))^s d_s$ , and  $a_{T+s+1} = \frac{1+\alpha}{\alpha}a_{T+s} - \frac{1}{\alpha}d_s$  for  $s \geq 1$ . When the fundamental follows a random walk,  $d_s = 1 \forall s$ , so that  $a_{T+s} = 1 \forall s \geq 1$ .

The fixed point problem in the parameters  $(a_1, a_2, \dots, a_T, b_1, \dots, b_{T+1})$  consists of  $2T+1$  equations. One of them is the  $b_{T+1} = -\alpha\gamma\sigma^2\rho_b^T/(1+\alpha-\alpha\rho_b)$ . The other  $2T$  equations equate the parameters of the conjectured and equilibrium exchange rate equations up to lag  $T-1$ . The conjectured parameters  $(a_1, a_2, \dots, a_T, b_1, \dots, b_{T+1})$ , together with the solution for  $a_{T+1}$  above allow us to compute  $\boldsymbol{\theta}$ ,  $\mathbf{H}$ ,  $\mathbf{M}$  and  $\sigma^2$ , and therefore the parameters of the equilibrium exchange rate equation. We use the Gauss NLSYS routine to solve the  $2T+1$  non-linear equations.

## C Higher Order Expectations

We show how (27) follows from Proposition 1 in Bacchetta and van Wincoop [2004a]. Bacchetta and van Wincoop [2004a] define the higher order wedge  $\Delta_t$  as the present value of deviations between higher order and first order expectations. In our application (assuming  $\rho_b = 0$ ):

$$\Delta_t = \sum_{s=2}^{\infty} \left( \frac{\alpha}{1+\alpha} \right)^s \left[ \bar{E}_t^s f_{t+s} - \bar{E}_t f_{t+s} \right] \quad (40)$$

Define  $PV_t = \sum_{s=1}^{\infty} \left( \frac{\alpha}{1+\alpha} \right)^s f_{t+s}$  as the present discounted value of future observed fundamentals. Let  $\mathbf{V}_t^i$  be the set of private signals available at time  $t$  that are still informative about  $PV_{t+1}$  at  $t+1$ . In our application  $\mathbf{V}_t^i = (v_{t-T+2}^i, \dots, v_t^i)'$ . Let  $\bar{\mathbf{V}}_t$  denote the average across investors of the vector  $\mathbf{V}_t^i$ . Proposition 1 of Bacchetta and van Wincoop [2004a] then says that

$$\Delta_t = \mathbf{\Pi}'_t (\bar{E}_t \bar{\mathbf{V}}_t - \bar{\mathbf{V}}_t) \quad (41)$$

where  $\mathbf{\Pi}_t = \frac{1}{R^2} (\mathbf{I} - \mathbf{\Psi})^{-1} \boldsymbol{\theta}$ ,  $\boldsymbol{\theta}' = \partial E_{t+1}^i PV_{t+1} / \partial \mathbf{V}_t^i$  and  $\mathbf{\Psi}' = \partial E_{t+1}^i \bar{\mathbf{V}}_{t+1} / \partial \mathbf{V}_t^i$ .

In our context  $\bar{\mathbf{V}}_t = (f_{t+2}, \dots, f_{t+T})$ . For  $\rho_b = 0$  equations (7), (40) and (41) then lead to (27) with  $\mathbf{\Pi}/(1+\alpha) = (\pi_2, \dots, \pi_T)'$ .

## D Order Flow

In this section we describe our measure of order flow when the observable fundamental follows a random walk. Using the notation and results from Appendix B, we have

$$b_{Ft}^i = \frac{\boldsymbol{\theta}' \mathbf{M} \mathbf{Y}_t^i + f_t - n b_{t-T} - s_t + i_t^* - i_t}{\gamma \sigma_t^2} - b_t^i \quad (42)$$

where  $n = \alpha \gamma \sigma^2 \rho_b^{T+1} / (1 + \alpha - \alpha \rho b)$ . Let  $\boldsymbol{\mu} = (\mu_1, \dots, \mu_T)'$  be the last  $T$  elements of  $\mathbf{M}' \boldsymbol{\theta}$ , divided by  $\gamma \sigma^2$ . The component of demand that depends on private information is therefore

$$\sum_{s=1}^T \mu_s v_{t+1-s}^{i*} - b_t^i. \quad (43)$$

Using that  $v_{t+1-s}^{i*} = \epsilon_{t+1}^f + \dots + \epsilon_{t+1-s+T}^f$ , (43) aggregates to

$$\boldsymbol{\eta}' \boldsymbol{\xi}_t - \rho_b^T b_{t-T} \quad (44)$$

where  $\boldsymbol{\eta}' = (\eta_1, \dots, \eta_{2T})$  with  $\eta_s = \mu_1 + \dots + \mu_s$  and  $\eta_{T+s} = -\rho_b^{s-1}$  for  $s = 1, \dots, T$ . Order flow  $x_t - x_{t-1}$  is defined as the component of (44) that is orthogonal to public information (other than  $s_t$ ). Public information that helps predict this term includes  $b_{t-T}$  and  $s_{t-1}^*, \dots, s_{t-T+1}^*$ . Order flow is then the error term of a regression of  $\boldsymbol{\eta}'\boldsymbol{\xi}_t$  on  $s_{t-1}^*, \dots, s_{t-T+1}^*$ . Defining  $\mathbf{H}_s$  as rows 2 to  $T$  of the matrix  $\mathbf{H}$  defined in Appendix B.2, it follows from Appendix B.2 that  $\bar{E}_t(\boldsymbol{\xi}_t | s_{t-1}^*, \dots, s_{t-T+1}^*) = \mathbf{M}_s \mathbf{H}'_s \boldsymbol{\xi}_t$ , where  $\mathbf{M}_s = \tilde{\mathbf{P}} \mathbf{H}_s [\mathbf{H}'_s \tilde{\mathbf{P}} \mathbf{H}_s]^{-1}$ . It follows that

$$x_t - x_{t-1} = \boldsymbol{\eta}'(\mathbf{I} - \mathbf{M}_s \mathbf{H}'_s) \boldsymbol{\xi}_t \quad (45)$$

It can also be shown that the exchange rate and cumulative order flow are not cointegrated. When  $f$  follows a random walk, the equilibrium exchange rate can be written as (see Appendix B.3)

$$s_t = f_t - \phi b_{t-T} + \boldsymbol{\tau}' \boldsymbol{\xi}_t \quad (46)$$

Order flow is equal to

$$x_t - x_{t-1} = \boldsymbol{\nu}' \boldsymbol{\xi}_t \quad (47)$$

where  $\boldsymbol{\nu}' = \boldsymbol{\eta}'(\mathbf{I} - \mathbf{M}_s \mathbf{H}'_s)$ . It therefore follows that cumulative order flow is equal to

$$x_t = (\nu_1 + \dots + \nu_T) f_t + (\nu_{T+1} + \dots + \nu_{2T}) \sum_{s=0}^{\infty} \varepsilon_{t-T-s}^b + \boldsymbol{\psi}' \boldsymbol{\xi}_t \quad (48)$$

where  $\boldsymbol{\psi}$  depends on the parameters in the vector  $\boldsymbol{\nu}$ . That the exchange rate is not cointegrated with cumulative order flow is due to the second term in the cumulative order flow equation. The coefficient on  $\varepsilon_{t-k}^b$  approaches zero in the exchange rate equation as  $k \rightarrow \infty$  (assuming  $\rho_b < 1$ ), while cumulative order flow depends on the infinite unweighted sum of all past innovations to hedge trades. When  $\rho_b = 1$ , so that aggregate hedge trades follow a random walk, hedge trades have a permanent effect on both the exchange rate and cumulative order flow. However, numerical analysis confirms that even in this case the exchange rate is not cointegrated with cumulative order flow since the ratio of the long-run effects of  $\varepsilon^b$  and  $\varepsilon^f$  shocks is different for the exchange rate than for cumulative order flow.

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	Benchmark parameterization
$\sigma_f$	0.01
$\sigma_b$	0.01
$\sigma_v$	0.08
$\rho_b$	0.8
$\alpha$	10
$\gamma$	500
$T$	8

Table 1: Parameterization