Financial Econometrics Research Centre

WORKING PAPERS SERIES

WP06-17

Dynamic instability in a phenomenological model of correlated assets

Giacomo Raffaelli and Matteo Marsili

Dynamic instability in a phenomenological model of correlated assets

Giacomo Raffaelli & Matteo Marsili
INFM-SISSA, via Beirut 2-4, Trieste I-34014, Italy and
Abdus Salam International Centre for Theoretical Physics
Strada Costiera 11, 34014 Trieste, Italy

We show that financial correlations exhibit a non-trivial dynamic behavior. We introduce a simple phenomenological model of a multi-asset financial market, which takes into account the impact of portfolio investment on price dynamics. This captures the fact that correlations determine the optimal portfolio but are affected by investment based on it. We show that such a feedback on correlations gives rise to an instability when the volume of investment exceeds a critical value. Close to the critical point the model exhibits dynamical correlations very similar to those observed in real markets. Maximum likelihood estimates of the model's parameter for empirical data indeed confirm this conclusion, thus suggesting that real markets operate close to a dynamically unstable point.

Financial markets – as prototypical examples of the collective effects of human interaction – have recently attracted the attention of many physicists. This is because, in spite of their internal complications, their aggregate behavior exhibits surprising regularities which can be cast in the form of simple, yet non-trivial, statistical laws[1, 2, 3], reminiscent of the scaling laws obeyed by anomalous fluctuations in critical phenomena. Such a suggestive indication has been put on even firmer basis by recent research on the statistical physics approach to interacting agent models[4, 5, 6, 7, 8]. This has shown that quite realistic market behavior can indeed be generated by the internal dynamics generated by traders' interaction.

The theoretical approach has, thus far, mostly concentrated on single asset models, whereas empirical analysis has shown that ensembles of assets exhibit rich and non-trivial statistical properties, whose relations with random matrix theory [9, 10], complex networks [11, 12] and multi-scaling [13] have attracted the interest of physicists. The central object of study is the covariance matrix of asset returns (at the daily scale in most cases). The bulk of its eigenvalue distribution is dominated by noise and described very well by random matrix theory [9]. The few large eigenvalues which leak out of the noise background contain significant information about market's structure. The taxonomy built with different methods [10, 14, 15] from financial correlations alone bear remarkable similarity with a classification in economic sectors. This agrees with the expectation that companies engaged in similar economic activities are subject to the same "factors", e.g. fluctuations in prices or demands of common inputs or outputs. Besides their structure, market correlations also exhibit a highly non-trivial dynamics: Correlations "build up" as the sampling time horizon on which returns are measured increases (Epps effect) and saturate for returns on the scale of some days [16]. Furthermore, these correlations are persistent over time [11] and they follow recurrent patterns [15].

In what follows we shall mostly concentrate on the dynamics of the largest eigenvalue of the correlation matrix. The corresponding *market mode* [9] describes the co-movement of stocks and it accounts for a significant fraction of the correlations[17]. Fig. 1a shows the time dependence of the largest eigenvalue of the (exponentially averaged) correlation matrix of daily returns for Toronto Stock Exchange [18]. Similar behavior has been reported earlier [19] for different markets. Fig. 2 shows that fluctuations in the largest eigenvalue are broadly distributed, suggesting that Fig. 1a can hardly be explained entirely as the effect of few external shocks.

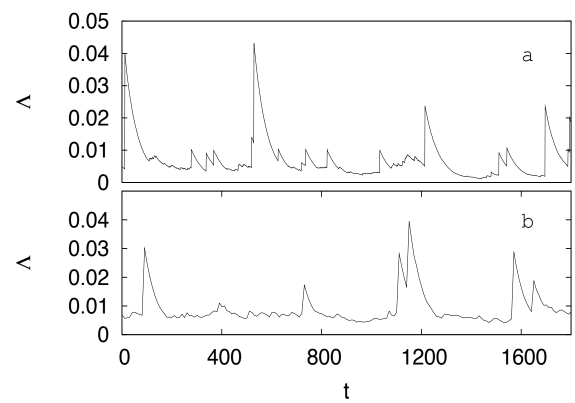

FIG. 1: Maximum eigenvalue of the correlation matrix as a function of time for $\tau = 50$. a) Toronto Stock exchange [18]. Here the correlation matrix is obtained using Eqs. (4) and (5) with $|\delta x_t\rangle$ taken from historical data. b) simulation of Eq.(1) with $N = 20$, $R = 5\,10^{-4}$, $B = 10^{-3}$,$\Delta = 1$,$\epsilon = 10^{-1}$, $W = 0.245$. Components of $|b\rangle$ where generated uniformly in the interval $[0, 2\cdot 10^{-3}]$, resulting in $W^* \approx 0.25$.

This leads us to formulate the hypothesis that such non-trivial behavior arises as a consequence of the internal market dynamics. One of the key functions of financial markets is indeed that of allowing companies to "trade" their risk for return, by spreading it across financial investors. Investors on their side, diversify (i.e. spread) their strategies across stocks so as to minimize risk, as postulated by portfolio optimization theory [20]. The efficiency of portfolio optimization depends on the cross correlations among the stocks the financial market is composed of. The optimal portfolio is computed under the *price taking* assumption that investment does not affect the market. While this is reasonable for the single investor, the effect of many investors following this same strategy can be

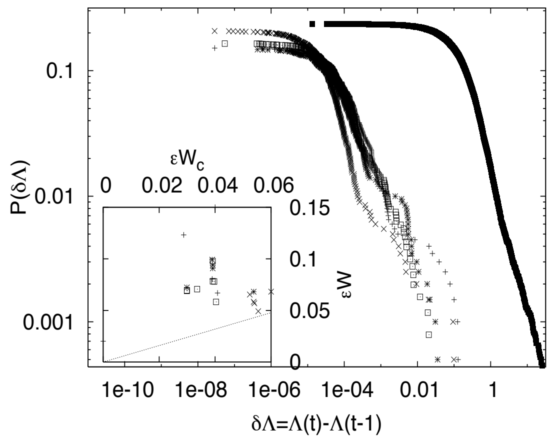

FIG. 2: Cumulative distribution of the day-to day change in the maximum eigenvalue for different indices: DAX $(+)$, TSX$(\star)$, DOW$(\square)$, ASX$(\times)$. Also shown is the same distribution for a numerical simulation of the model with $N = 20$, $\epsilon = 0.1$, $R = 1$, $W = 14.7$, $\Delta = 1$,$B = 10^{-2}$,$\tau = 100$. In the inset we show the results of the fitting procedure on these indices (same symbols).

sizeable. If financial trading activity resulting from portfolio optimization strategies have an impact on prices' dynamics, it will also affect the correlations which these strategies exploit. Hence financial correlations enter into a feedback loop because they determine in part those trading strategies which contribute to the price dynamics, i.e. to the financial correlations themselves. This feedback is somewhat implicit in the Capital Asset Pricing Model (CAPM), which concludes that since all traders invest according to the optimal portfolio, the market is well approximated by a one factor model [20] (see however [12]). While this explains why the largest eigenvalue of the correlation matrix is so well separated from the other ones, CAPM relies on rational expectation equilibrium arguments, and it does not address dynamical effects such as those of Fig. 1a.

This Letter discusses a general phenomenological approach, in the spirit of Landau's theory of critical phenomena [21], which shows that a non-trivial dynamics of correlations can indeed result from the internal dynamics due to trading on optimal portfolio strategies. The model predicts a dynamical instability if the investment volume W exceeds a critical value. Not only we find very realistic dynamics of correlations close to the critical point (see Fig. 1b) but maximum likelihood parameter estimation from real data suggest that markets are indeed close to the instability. Phenomenological models are particularly suited for modeling complex systems, such as a financial market, were a bottom-up (microscopic) approach inevitably implies dealing with many complications and introducing *ad hoc* assumptions [23]. For the ease of exposition, we shall first introduce a minimal model which captures the interaction among assets induced by portfolio investment. Later we will show that this model contains the lowerst order terms in a general expansion of the dynamics and that all the terms beyond these are irrelevant as far as the main conclusions are concerned. A further reason for focusing on the simplest model is that it will make the comparison with empirical data easier.

Let us consider a set of N assets. We denote by $|x\rangle$ the vector of log-prices and use bra-ket notation [22]. We focus on daily time-scale and assume that $|x_t\rangle$ undergoes the dynamics

$$|x_{t+1}\rangle = |x_t\rangle + |\beta_t\rangle + \xi_t|z_t\rangle. \tag{1}$$

where $|\beta_t\rangle$ is the vector of *bare* returns, which describes all *external* "forces" which drive the prices, including economic processes. This is assumed to be a Gaussian random vector with

$$E[|\beta_t\rangle] = |b\rangle, \qquad E[|\beta_t\rangle\langle\beta(t')|] = |b\rangle\langle b| + \hat{B}\delta_{t,t'} \tag{2}$$

$|b\rangle$ and $\hat{B}$ will be considered as parameters in what follows.

The last term of Eq. (1) describes the impact of portfolio investment on the price dynamics: ξ_t is an independent Gaussian variable with mean ϵ and variance Δ and the vector $|z_t\rangle$ is the optimal portfolio with fixed return R and total wealth $\langle z|1\rangle = W$. In other words, $|z_t\rangle$ is the solution of

$$\min_{|z\rangle,\nu,\sigma}\left[\frac{1}{2}\langle z|\hat{C}_t|z\rangle - \nu\left(\langle z|r_t\rangle - R\right) - \sigma\left(\langle z|1\rangle - W\right)\right] \tag{3}$$

where $\hat{C}_t$ is the correlation matrix at time t. Both the expected returns $|r_t\rangle$ and the correlation matrix $\hat{C}_t$, which enter Eq. (3), are computed from historical data over a characteristic time τ:

$$|r_t\rangle \;=\; (e^{\frac{1}{\tau}}-1)\sum_{t'<t} e^{-\frac{t-t'}{\tau}}|\delta x_t\rangle \tag{4}$$

$$\hat{C}_t \;=\; (e^{\frac{1}{\tau}}-1)\sum_{t'<t} e^{-\frac{t-t'}{\tau}}|\delta x_t\rangle\langle\delta x_t| - |r_t\rangle\langle r_t| \tag{5}$$

where $|\delta x_t\rangle \equiv |x_{t+1}\rangle - |x_t\rangle$ [24]. This makes the set of equations above a self-contained dynamical stochastic system. In a nutshell, it describes how the economic *bare* correlated fluctuations $|\beta_t\rangle$ are *dressed* by the trading activity due to investment in optimal portfolio strategies. R, W, Δ and τ are *phenomenological* parameters reflecting the portfolio composition which dominates trading activity, not necessarily those of a representative investor. In particular, note that $|z_t\rangle$ is a quantity, not a percentage as in portfolio theory [20]. Indeed, the impact of investment on prices depends on the volume of transactions. The parameter W, which can be taken as a proxy for the volume of trading on portfolio strategies, will play a crucial role in what follows.

These parameters are assumed to be constant, meaning that portfolio policies change over time-scales much longer than τ. Portfolio theory is, in principle, based on expected returns and covariances. We implicitely assume that historical data can be used as a proxy for expected correlations and returns. Eqs. (1–5) also assume that portfolio investment is dominated by a single time scale τ. Later we shall argue that a generic distribution of time scales would not change the main results. Finally, Eq. (1) assumes a linear price impact and gaussian *bare* returns. Both assumptions may be questionable, specially at high frequency [25, 26]. We shall see, however, that non-trivial dynamics and statistics (including a fat tailed distribution of returns) arises even in such a simplified setting, thus suggesting that the specific market mechanism and the statistics of *bare* returns are unessential ingredients.

Numerical simulations of the model show a very interesting behavior. In Fig 1b we plot the temporal evolution of the maximum eigenvalue of the correlation matrix for a particular choice of parameters (see later). The dynamics is highly non-trivial, with the appearance of instabilities resembling those observed for real markets (Fig. 1a). To be more precise, we also analyze the statistics of the day-to-day differences in Λ. In Fig. 2 we can see a clear power-law behavior emerging, again very similar to the one we get for real markets.

In order to shed light on these findings, let us consider the behavior of the model in the limit $\tau \to \infty$. We assume that, in this limit, the correlations and hence $|z_t\rangle$ reach a time independent limit, which by Eqs. $(1, 3)$ is given by

$$|z\rangle = \frac{1}{\hat{C} - \nu\epsilon} \left(\nu|b\rangle + \sigma|1\rangle\right) \tag{6}$$

where σ and ν are fixed by the constraints $\langle z|1\rangle = W$ and $\langle z|r\rangle = R$. Notice that $|r\rangle = E[|\delta x\rangle] = |b\rangle + \epsilon|z\rangle$ needs to be determined self-consistently. We find $\hat{C} = \hat{B} + \Delta|z\rangle\langle z|$ which, combined with Eq. (6), yields an equation for $\hat{C}$. In order to make the analysis simpler, we assume structure-less *bare* correlations $\hat{B} = B\hat{I}$. In this case $\hat{C}$ has $N-1$ eigenvalues equal to B, and one eigenvalue with eigenvector parallel to $|z\rangle$, whose value is [27]

$$\Lambda = B + \frac{\Delta W^2}{N} + \frac{N\overline{\delta b^2}\Delta(1-\sqrt{1-a})^2}{4\epsilon} \tag{7}$$

where $a = 4[W(\overline{b} + \epsilon W/N) - R]/(N\overline{\delta b^2})$ and $\overline{b}$, $\overline{\delta b^2}$ are the average and the variance of *bare* returns, respectively. If R and W are both proportional to N, then the contribution to Λ due to portfolio investment is also proportional to N. This is indeed the order of Λ in empirical data. Most remarkably, Eq. (7) makes sense only for $a < 1/4$, i.e. for

$$W < W^* = \frac{N}{2\epsilon}\left[\sqrt{\overline{b^2} + \frac{4\epsilon R}{N}} - \overline{b}\right]. \tag{8}$$

As $W \to W^*$ the solution develops a singularity with infinite slope $\frac{\partial \Lambda}{\partial W} \to \infty$. This is reminiscent of the divergence of susceptibility χ close to a phase transition, signalling that the response $\delta\Lambda = \chi\delta W$ to a small perturbation δW diverges as $W \to W^*$. The origin of the singularity at W^* is directly related to the impact of portfolio investment. Indeed, notice that the two constraints are hyper-planes in the space of portfolios $|z\rangle$ when $\epsilon = 0$ and always have a non-empty intersection. When $\epsilon > 0$, the constraint on return becomes an hyper-sphere, centered in $-|b\rangle/(2\epsilon)$ and of radius $\sqrt{\langle b|b\rangle/4 + \epsilon R}/\epsilon$. Hence intersections exist only for $W < W^*$.

As anticipated, Eq. (1) can be thought of as the lowest order of a phenomenological expansion [21]. Higher orders, e.g. $|z_{t+1}\rangle - |z_t\rangle$, as well as terms proportional to $|r_t\rangle$ and its time derivatives, can be included. Likewise, one can consider a generic matrix $\hat{B}$, or add several components $|z_t^k\rangle$ of portfolio investment in Eq. (1), each with different parameters R^k, W^k and Δ^k or acting over different time horizons τ_k. In all these case, we confirmed [28] the existence of a dynamical instability when the volume of trading exceeds a critical value, as long as the time-scales (τ_k) over which averages are taken in Eqs. (4,5) are very large. The analytic approach can be extended to finite τ by a systematic $1/\tau$ expansion in the $W < W^*$ phase [28]. This expansion describes how fluctuations in slow quantities, such as $|z_t\rangle$ or $\hat{C}_t$ vanish as $\tau \to \infty$. We find that the coefficients of the $1/\sqrt{\tau}$ expansion diverge as $W \to W^*$, signalling that fluctuations do not vanish for $W > W^*$. For example, we find that fluctuations in Λ diverge as $\delta\Lambda \sim |W^* - W|^{-1/2}$, when $W \to W^*$. This is why higher order terms such as $|z_t\rangle - |z_{t-1}\rangle$ in Eq. (1) are irrelevant, in the sense of critical phenomena, i.e. their presence does not affect the occurrence of the phase transition.

Numerical simulations fully confirm these results. Fig. 3 reports the relative fluctuations of Λ_t as a function of W, for simulations carried out at different time scales τ. For $W < W^*$, fluctuations vanish as τ increases and Λ converges to the value of Eq. (7). For $W > W^*$, instead, the dynamics is characterized by persistent instabilities with fluctuations of the same order of Λ, and it does not attain a smooth limit as $\tau \to \infty$. For values of W smaller but close to W^* the model exhibits strong fluctuations, precursors of the instabilities for $W > W^*$. It is precisely in this critical region that we recover realistic results, such as those of Fig 1b. Moreover, the distribution of returns develops a power law behavior as W approaches W^* (with a cutoff which diverges as $1/\sqrt{W^* - W}$).

The presence of a phase transition from a stable to an unstable state and the strong resemblance of the dynamics of the model close to criticality with real data (see Fig. 1) suggests that real markets might be close to the phase transition. In order to investigate this issue systematically, we estimate the parameters of our model from real data. In doing this we implicitly assume that parameters ϵ, R, W etc. vary slowly on time scales of order τ. We compute the likelihood that the particular set of time series of a given market are produced as output of Eq. (1) for a particular choice of parameters. Next we find the parameters which maximize the likelihood [28]. As a check, the procedure was run on synthetic data set generated by Eq. (1) and it allowed us to recover the parameters with which the data set was created. In the inset of Fig. 2 we plot the result of such a fit for (the assets of) four different indices in the time period 1997-2005 [18]. We used $\tau = 50$ and fits were taken on a time window of $T = 300$ days. Notice, in this respect, that while in our model τ enters both in the dynamics and in the way we take averages, in the empirical analysis it only enters in the way we take averages, whereas we don't have access to the time scale τ used by investors. We checked that the main results do not depend significantly on the choice of τ. We see that fitted parameters for real markets tend to cluster close, but below, the transition line $W = W^*$. This is also consistent with the similarity of the distribution of Λ for real and synthetic data of Fig. 2.

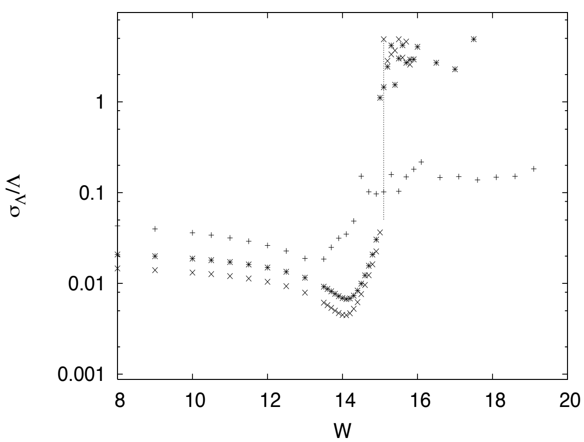

FIG. 3: Relative fluctuation of the maximum eigenvalue as a function of W in a simulation of the model with $N = 20$, $\epsilon = 0.1$, $R = 1$, $\Delta = 1$,$B = 10^{-2}$,$\tau = 1000$ (+), $\tau = 20000$ ($\times$) and $\tau = 50000$ ($\star$). Vertical line is the theoretical critical value of W.

Our model is very stylized and it misses many important aspects. For example, it is undeniable that external factors and global events have an effect on financial markets. For example, the introduction of the Euro has a visible effect on the scatter of points for the DAX in the inset of Fig. 2. On the other hand, the points relative to non-European markets in different time windows cluster in the same region, showing that parameters can indeed be considered as roughly constant on the time-scales discussed here. At any rate, rather than insisting on the validity of the model on theoretical grounds, we have shown that it reproduces key empirical features of real financial markets. This makes us conjecture that a sizeable contribution to the collective behavior of markets arises from its internal dynamics and that this is a potential cause of instability. If, following Ref. [29], crashes were activated events triggered by large fluctuations, the proximity to the instability would make the occurrence of such correlated fluctuations more likely, thus enhancing the likelihood of crashes.

Our results indicate the existence of an additional component of risk due to the enhanced susceptibility of the market. Such "market impact" risk arises because investing in risk minimization strategies affects the structure of correlations with which those strategies were computed. This component of risk diverges as the market approaches the critical point W^*, thus discouraging further investment. This provides a simple rationale of why markets "self-organize" close to the critical point. Such a scenario is reminiscent of the picture which Minority Games [8] provide of single asset markets as systems driven to a critical state, by speculative trading [30]. In both cases, the action of traders (either to exploit predictable patterns or to minimize risk) produces a shift in the position of the equilibrium that counteracts the effect of this action (by either making the market less predictable or more risky), as if a sort of generalized Le Chatelier's principle were at play.

[1] J.-P. Bouchaud and M. Potters *Theory of financial risk and derivative pricing: from statistical physics to risk management* (Cambridge University Press, Cambridge, 2003).

[2] R. Mantegna and E. Stanley, *Introduction to Econophysics* (Cambridge University Press, 1999)

[3] M. M. Dacorogna, *et al. An Introduction to High-Frequency Finance*, Chap. V, Academic Press, London (2001)

[4] Caldarelli G., Marsili M. and Zhang Y-C., Europhys. Lett. **40**, 479 (1997)

[5] Lux T. and Marchesi M., Nature **397** (6719) 498-500 (1999)

[6] R. Cont and J.-P. Bouchaud, Macroecon. Dyn. **4**, 170 (2000).

[7] H. Levy, M. Levy, S. Solomon, *From Investor Behaviour to Market Phenomena*, Academic Press, London (2000).

[8] Challet D., Marsili M. and Zhang Y-C. *Minority Games. Interacting agents in financial markets* Oxford University Press (Oxford, 2004)

[9] Laloux L, *et al.*, Phys. Rev. Lett. **83** 1467 (1999); Plerou V, *et al.*, Phys. Rev. Lett. **83** 1471 (1999)

[10] Plerou V, *et al.* Phys. Rev. E **65** 066126 (2002).

[11] Onnela JP, *et al.*, Phys. Rev. E **68** 056110 (2003)

[12] Bonanno G., *et al.*, Phys. Rev. E **68** 046130 (2003).

[13] Z. Eisler, *et al.* Europhys. Lett. **69**, 664 (2005).

[14] Mantegna RN, Eur. Phys. J. B, **11**, 193 (1999).

[15] Marsili M. Quant. Fin. **2** 297 (2002)

[16] Kwapien J, Drozdz S. and Speth J, Phys. A **330** 605 (2003); G. Bonanno, F. Lillo and R. N. Mantegna, Quant. Fin. **1** 96 (2001)

[17] The persistence of the structure of correlations [11, 14] and their overlap with economic sectors [10, 15] suggests that it can be related to economic factors which evolve on long time scales. Financial activity is instead relevant over time scales of few days and it is responsible for the emergence of the market mode.

[18] Data was taken form `finance.yahoo.com` in the time period June $16^{\rm th}$ 1997 to May $25^{\rm th}$ 2005 for all assets except for the Dow Jones, for which we used May $2^{\rm nd}$ 1995 to May $23^{\rm rd}$ 2005. Correlations were measured on the set of assets composing the index at the final date.

[19] Drodz S, em et al.,Physica A **294**, 226 (2001).

[20] Elton E.J. and Gruber M.J., *Modern Portfolio theory and investment analysis* (J. Wiley & sons, New York, 1995).

[21] Landau, L. D., in *Collected Papers of L. D. Landau* (ed. ter Haar, D.) 193-216 (Pergamon, Oxford, 1965).

[22] $|x\rangle$ should be considered as a column vector, whereas $\langle x|$ is a row vector. Hence $\langle x|y\rangle$ is the scalar product and $|x\rangle\langle y|$ is the direct product, i.e. the matrix with entries $a_{i,j} = x_i y_j$.

[23] A simple generalization of single asset market models [5, 8] might also produce a complex dynamics. The emergence of a market mode is a natural consequence of *ad hoc* behavioral assumptions (herding). Such an approch, however, focuses on

speculative trading where the dynamicsis driven by expected returns, and misses the peculiar role which risk and correlations play.

[24] Exponential moving averages such as that used in Eqs. (4,5) are widely used in finance (see [20] p. 59). Our main results are related to the behavior of the model for $\tau \to \infty$ and clearly remain unchanged if one assumes uniform averages over a finite window T (as e.g. Refs. [11, 12, 14, 15]), and then lets $T \to \infty$.

[25] Gabaix X., *et al.*, Nature **423** 267-270 (2003) and Lillo F., Farmer J. D., Mantegna R. N., Nature **421** 129-130 (2003).

[26] Farmer, J.D. Ind. & Corp. Change **11**, 895 (2002)

[27] There are indeed two solutions for Λ. We choose the one for which $\Lambda \to B$ as $\epsilon \to 0$.

[28] Raffaelli G., Ponsot B. and Marsili M., in preparation.

[29] R. Cont and J.-P. Bouchaud, Eur. Phys. J. B **6**, 543 (1998).

[30] Challet D. and Marsili M. Phys. Rev. E **68** (3) 036132 (2003)

List of other working papers:

2006

1. Roman Kozhan, Multiple Priors and No-Transaction Region, WP06-24
2. Martin Ellison, Lucio Sarno and Jouko Vilmunen, Caution and Activism? Monetary Policy Strategies in an Open Economy, WP06-23
3. Matteo Marsili and Giacomo Raffaelli, Risk bubbles and market instability, WP06-22
4. Mark Salmon and Christoph Schleicher, Pricing Multivariate Currency Options with Copulas, WP06-21
5. Thomas Lux and Taisei Kaizoji, Forecasting Volatility and Volume in the Tokyo Stock Market: Long Memory, Fractality and Regime Switching, WP06-20
6. Thomas Lux, The Markov-Switching Multifractal Model of Asset Returns: GMM Estimation and Linear Forecasting of Volatility, WP06-19
7. Peter Heemeijer, Cars Hommes, Joep Sonnemans and Jan Tuinstra, Price Stability and Volatility in Markets with Positive and Negative Expectations Feedback: An Experimental Investigation, WP06-18
8. Giacomo Raffaelli and Matteo Marsili, Dynamic instability in a phenomenological model of correlated assets, WP06-17
9. Ginestra Bianconi and Matteo Marsili, Effects of degree correlations on the loop structure of scale free networks, WP06-16
10. Pietro Dindo and Jan Tuinstra, A Behavioral Model for Participation Games with Negative Feedback, WP06-15
11. Ceek Diks and Florian Wagener, A weak bifucation theory for discrete time stochastic dynamical systems, WP06-14
12. Markus Demary, Transaction Taxes, Traders' Behavior and Exchange Rate Risks, WP06-13
13. Andrea De Martino and Matteo Marsili, Statistical mechanics of socio-economic systems with heterogeneous agents, WP06-12
14. William Brock, Cars Hommes and Florian Wagener, More hedging instruments may destabilize markets, WP06-11
15. Ginwestra Bianconi and Roberto Mulet, On the flexibility of complex systems, WP06-10
16. Ginwestra Bianconi and Matteo Marsili, Effect of degree correlations on the loop structure of scale-free networks, WP06-09
17. Ginwestra Bianconi, Tobias Galla and Matteo Marsili, Effects of Tobin Taxes in Minority Game Markets, WP06-08
18. Ginwestra Bianconi, Andrea De Martino, Felipe Ferreira and Matteo Marsili, Multi-asset minority games, WP06-07
19. Ba Chu, John Knight and Stephen Satchell, Optimal Investment and Asymmetric Risk for a Large Portfolio: A Large Deviations Approach, WP06-06
20. Ba Chu and Soosung Hwang, The Asymptotic Properties of AR(1) Process with the Occasionally Changing AR Coefficient, WP06-05
21. Ba Chu and Soosung Hwang, An Asymptotics of Stationary and Nonstationary AR(1) Processes with Multiple Structural Breaks in Mean, WP06-04
22. Ba Chu, Optimal Long Term Investment in a Jump Diffusion Setting: A Large Deviation Approach, WP06-03
23. Mikhail Anufriev and Gulio Bottazzi, Price and Wealth Dynamics in a Speculative Market with Generic Procedurally Rational Traders, WP06-02
24. Simonae Alfarano, Thomas Lux and Florian Wagner, Empirical Validation of Stochastic Models of Interacting Agents: A "Maximally Skewed" Noise Trader Model?, WP06-01

2005

1. Shaun Bond and Soosung Hwang, Smoothing, Nonsynchronous Appraisal and Cross-Sectional Aggreagation in Real Estate Price Indices, WP05-17

2. Mark Salmon, Gordon Gemmill and Soosung Hwang, Performance Measurement with Loss Aversion, WP05-16
3. Philippe Curty and Matteo Marsili, Phase coexistence in a forecasting game, WP05-15
4. Matthew Hurd, Mark Salmon and Christoph Schleicher, Using Copulas to Construct Bivariate Foreign Exchange Distributions with an Application to the Sterling Exchange Rate Index (Revised), WP05-14
5. Lucio Sarno, Daniel Thornton and Giorgio Valente, The Empirical Failure of the Expectations Hypothesis of the Term Structure of Bond Yields, WP05-13
6. Lucio Sarno, Ashoka Mody and Mark Taylor, A Cross-Country Financial Accelorator: Evidence from North America and Europe, WP05-12
7. Lucio Sarno, Towards a Solution to the Puzzles in Exchange Rate Economics: Where Do We Stand?, WP05-11
8. James Hodder and Jens Carsten Jackwerth, Incentive Contracts and Hedge Fund Management, WP05-10
9. James Hodder and Jens Carsten Jackwerth, Employee Stock Options: Much More Valuable Than You Thought, WP05-09
10. Gordon Gemmill, Soosung Hwang and Mark Salmon, Performance Measurement with Loss Aversion, WP05-08
11. George Constantinides, Jens Carsten Jackwerth and Stylianos Perrakis, Mispricing of S&P 500 Index Options, WP05-07
12. Elisa Luciano and Wim Schoutens, A Multivariate Jump-Driven Financial Asset Model, WP05-06
13. Cees Diks and Florian Wagener, Equivalence and bifurcations of finite order stochastic processes, WP05-05
14. Devraj Basu and Alexander Stremme, CAY Revisited: Can Optimal Scaling Resurrect the (C)CAPM?, WP05-04
15. Ginwestra Bianconi and Matteo Marsili, Emergence of large cliques in random scale-free networks, WP05-03
16. Simone Alfarano, Thomas Lux and Friedrich Wagner, Time-Variation of Higher Moments in a Financial Market with Heterogeneous Agents: An Analytical Approach, WP05-02
17. Abhay Abhayankar, Devraj Basu and Alexander Stremme, Portfolio Efficiency and Discount Factor Bounds with Conditioning Information: A Unified Approach, WP05-01

2004

1. Xiaohong Chen, Yanqin Fan and Andrew Patton, Simple Tests for Models of Dependence Between Multiple Financial Time Series, with Applications to U.S. Equity Returns and Exchange Rates, WP04-19
2. Valentina Corradi and Walter Distaso, Testing for One-Factor Models versus Stochastic Volatility Models, WP04-18
3. Valentina Corradi and Walter Distaso, Estimating and Testing Sochastic Volatility Models using Realized Measures, WP04-17
4. Valentina Corradi and Norman Swanson, Predictive Density Accuracy Tests, WP04-16
5. Roel Oomen, Properties of Bias Corrected Realized Variance Under Alternative Sampling Schemes, WP04-15
6. Roel Oomen, Properties of Realized Variance for a Pure Jump Process: Calendar Time Sampling versus Business Time Sampling, WP04-14
7. Richard Clarida, Lucio Sarno, Mark Taylor and Giorgio Valente, The Role of Asymmetries and Regime Shifts in the Term Structure of Interest Rates, WP04-13
8. Lucio Sarno, Daniel Thornton and Giorgio Valente, Federal Funds Rate Prediction, WP04-12
9. Lucio Sarno and Giorgio Valente, Modeling and Forecasting Stock Returns: Exploiting the Futures Market, Regime Shifts and International Spillovers, WP04-11
10. Lucio Sarno and Giorgio Valente, Empirical Exchange Rate Models and Currency Risk: Some Evidence from Density Forecasts, WP04-10
11. Ilias Tsiakas, Periodic Stochastic Volatility and Fat Tails, WP04-09
12. Ilias Tsiakas, Is Seasonal Heteroscedasticity Real? An International Perspective, WP04-08
13. Damin Challet, Andrea De Martino, Matteo Marsili and Isaac Castillo, Minority games with finite score memory, WP04-07
14. Basel Awartani, Valentina Corradi and Walter Distaso, Testing and Modelling Market Microstructure Effects with an Application to the Dow Jones Industrial Average, WP04-06

15. Andrew Patton and Allan Timmermann, Properties of Optimal Forecasts under Asymmetric Loss and Nonlinearity, WP04-05
16. Andrew Patton, Modelling Asymmetric Exchange Rate Dependence, WP04-04
17. Alessio Sancetta, Decoupling and Convergence to Independence with Applications to Functional Limit Theorems, WP04-03
18. Alessio Sancetta, Copula Based Monte Carlo Integration in Financial Problems, WP04-02
19. Abhay Abhayankar, Lucio Sarno and Giorgio Valente, Exchange Rates and Fundamentals: Evidence on the Economic Value of Predictability, WP04-01

2002

1. Paolo Zaffaroni, Gaussian inference on Certain Long-Range Dependent Volatility Models, WP02-12
2. Paolo Zaffaroni, Aggregation and Memory of Models of Changing Volatility, WP02-11
3. Jerry Coakley, Ana-Maria Fuertes and Andrew Wood, Reinterpreting the Real Exchange Rate - Yield Diffential Nexus, WP02-10
4. Gordon Gemmill and Dylan Thomas , Noise Training, Costly Arbitrage and Asset Prices: evidence from closed-end funds, WP02-09
5. Gordon Gemmill, Testing Merton's Model for Credit Spreads on Zero-Coupon Bonds, WP02-08
6. George Christodoulakis and Steve Satchell, On th Evolution of Global Style Factors in the MSCI Universe of Assets, WP02-07
7. George Christodoulakis, Sharp Style Analysis in the MSCI Sector Portfolios: A Monte Caro Integration Approach, WP02-06
8. George Christodoulakis, Generating Composite Volatility Forecasts with Random Factor Betas, WP02-05
9. Claudia Riveiro and Nick Webber, Valuing Path Dependent Options in the Variance-Gamma Model by Monte Carlo with a Gamma Bridge, WP02-04
10. Christian Pedersen and Soosung Hwang, On Empirical Risk Measurement with Asymmetric Returns Data, WP02-03
11. Roy Batchelor and Ismail Orgakcioglu, Event-related GARCH: the impact of stock dividends in Turkey, WP02-02
12. George Albanis and Roy Batchelor, Combining Heterogeneous Classifiers for Stock Selection, WP02-01

2001

1. Soosung Hwang and Steve Satchell , GARCH Model with Cross-sectional Volatility; GARCHX Models, WP01-16
2. Soosung Hwang and Steve Satchell, Tracking Error: Ex-Ante versus Ex-Post Measures, WP01-15
3. Soosung Hwang and Steve Satchell, The Asset Allocation Decision in a Loss Aversion World, WP01-14
4. Soosung Hwang and Mark Salmon, An Analysis of Performance Measures Using Copulae, WP01-13
5. Soosung Hwang and Mark Salmon, A New Measure of Herding and Empirical Evidence, WP01-12
6. Richard Lewin and Steve Satchell, The Derivation of New Model of Equity Duration, WP01-11
7. Massimiliano Marcellino and Mark Salmon, Robust Decision Theory and the Lucas Critique, WP01-10
8. Jerry Coakley, Ana-Maria Fuertes and Maria-Teresa Perez, Numerical Issues in Threshold Autoregressive Modelling of Time Series, WP01-09
9. Jerry Coakley, Ana-Maria Fuertes and Ron Smith, Small Sample Properties of Panel Time-series Estimators with I(1) Errors, WP01-08
10. Jerry Coakley and Ana-Maria Fuertes, The Felsdtein-Horioka Puzzle is Not as Bad as You Think, WP01-07
11. Jerry Coakley and Ana-Maria Fuertes, Rethinking the Forward Premium Puzzle in a Non-linear Framework, WP01-06
12. George Christodoulakis, Co-Volatility and Correlation Clustering: A Multivariate Correlated ARCH Framework, WP01-05

13. Frank Critchley, Paul Marriott and Mark Salmon, On Preferred Point Geometry in Statistics, WP01-04
14. Eric Bouyé and Nicolas Gaussel and Mark Salmon, Investigating Dynamic Dependence Using Copulae, WP01-03
15. Eric Bouyé, Multivariate Extremes at Work for Portfolio Risk Measurement, WP01-02
16. Erick Bouyé, Vado Durrleman, Ashkan Nikeghbali, Gael Riboulet and Thierry Roncalli, Copulas: an Open Field for Risk Management, WP01-01

2000

1. Soosung Hwang and Steve Satchell , Valuing Information Using Utility Functions, WP00-06
2. Soosung Hwang, Properties of Cross-sectional Volatility, WP00-05
3. Soosung Hwang and Steve Satchell, Calculating the Miss-specification in Beta from Using a Proxy for the Market Portfolio, WP00-04
4. Laun Middleton and Stephen Satchell, Deriving the APT when the Number of Factors is Unknown, WP00-03
5. George A. Christodoulakis and Steve Satchell, Evolving Systems of Financial Returns: Auto-Regressive Conditional Beta, WP00-02
6. Christian S. Pedersen and Stephen Satchell, Evaluating the Performance of Nearest Neighbour Algorithms when Forecasting US Industry Returns, WP00-01

1999

1. Yin-Wong Cheung, Menzie Chinn and Ian Marsh, How do UK-Based Foreign Exchange Dealers Think Their Market Operates?, WP99-21
2. Soosung Hwang, John Knight and Stephen Satchell, Forecasting Volatility using LINEX Loss Functions, WP99-20
3. Soosung Hwang and Steve Satchell, Improved Testing for the Efficiency of Asset Pricing Theories in Linear Factor Models, WP99-19
4. Soosung Hwang and Stephen Satchell, The Disappearance of Style in the US Equity Market, WP99-18
5. Soosung Hwang and Stephen Satchell, Modelling Emerging Market Risk Premia Using Higher Moments, WP99-17
6. Soosung Hwang and Stephen Satchell, Market Risk and the Concept of Fundamental Volatility: Measuring Volatility Across Asset and Derivative Markets and Testing for the Impact of Derivatives Markets on Financial Markets, WP99-16
7. Soosung Hwang, The Effects of Systematic Sampling and Temporal Aggregation on Discrete Time Long Memory Processes and their Finite Sample Properties, WP99-15
8. Ronald MacDonald and Ian Marsh, Currency Spillovers and Tri-Polarity: a Simultaneous Model of the US Dollar, German Mark and Japanese Yen, WP99-14
9. Robert Hillman, Forecasting Inflation with a Non-linear Output Gap Model, WP99-13
10. Robert Hillman and Mark Salmon , From Market Micro-structure to Macro Fundamentals: is there Predictability in the Dollar-Deutsche Mark Exchange Rate?, WP99-12
11. Renzo Avesani, Giampiero Gallo and Mark Salmon, On the Evolution of Credibility and Flexible Exchange Rate Target Zones, WP99-11
12. Paul Marriott and Mark Salmon, An Introduction to Differential Geometry in Econometrics, WP99-10
13. Mark Dixon, Anthony Ledford and Paul Marriott, Finite Sample Inference for Extreme Value Distributions, WP99-09
14. Ian Marsh and David Power, A Panel-Based Investigation into the Relationship Between Stock Prices and Dividends, WP99-08
15. Ian Marsh, An Analysis of the Performance of European Foreign Exchange Forecasters, WP99-07
16. Frank Critchley, Paul Marriott and Mark Salmon, An Elementary Account of Amari's Expected Geometry, WP99-06
17. Demos Tambakis and Anne-Sophie Van Royen, Bootstrap Predictability of Daily Exchange Rates in ARMA Models, WP99-05
18. Christopher Neely and Paul Weller, Technical Analysis and Central Bank Intervention, WP99-04
19. Christopher Neely and Paul Weller, Predictability in International Asset Returns: A Re-examination, WP99-03

20. Christopher Neely and Paul Weller, Intraday Technical Trading in the Foreign Exchange Market, WP99-02
21. Anthony Hall, Soosung Hwang and Stephen Satchell, Using Bayesian Variable Selection Methods to Choose Style Factors in Global Stock Return Models, WP99-01

1998

1. Soosung Hwang and Stephen Satchell, Implied Volatility Forecasting: A Compaison of Different Procedures Including Fractionally Integrated Models with Applications to UK Equity Options, WP98-05
2. Roy Batchelor and David Peel, Rationality Testing under Asymmetric Loss, WP98-04
3. Roy Batchelor, Forecasting T-Bill Yields: Accuracy versus Profitability, WP98-03
4. Adam Kurpiel and Thierry Roncalli , Option Hedging with Stochastic Volatility, WP98-02
5. Adam Kurpiel and Thierry Roncalli, Hopscotch Methods for Two State Financial Models, WP98-01