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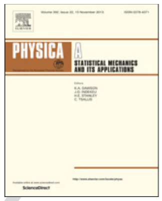

Q1
The roles of mean residence time on herd behavior in a financial market☆

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HIGHLIGHTS

- We investigate the herd behavior of stock prices in a finance system with the Heston model.
- The parameters are estimated based on real financial data.
- The mean residence time of positive return has been analyzed.
- A phenomenon of herd behavior is observed for both the theoretical and empirical case.

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ABSTRACT

We investigate the herd behavior of stock prices in a finance system with the Heston model. Based on parameter estimation of the Heston model obtained by minimizing the mean square deviation between the theoretical and empirical return distributions, we simulate mean residence time of positive return (MRTPR). Plots of MRTPR against the amplitude or mean reversion of volatility demonstrate a phenomenon of herd behavior for a positive cross correlation between noise sources of the Heston model. Also, for a negative cross correlation, a phenomenon of herd behavior is observed in plots of MRTPR against the long-run variance by increasing amplitude or mean reversion of volatility.

1. Introduction

A geometric Brownian motion model [1,2] was early proposed to depict the stochastic dynamics of stock prices in econophysics [3,4]. However, the model was widely criticized for its fat tails [4,5], long range memory and clustering of volatility [6]. To this end, some new models such as the Black–Scholes option pricing model [7], ARCH model [8], GARCH model [9] and Heston model [10] are developed to study dynamics of stock prices. Particularly, the Heston model, consisting of two coupled stochastic differential equations: the log-normal geometric Brownian motion stock process and the Cox–Ingersoll–Ross mean-reverting process, has received considerable attention over the past years. For example, Drăgulescu and Yakovenko [11] studied the time-dependent probability distribution of stock price returns in the Heston Q3

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model with stochastic volatility; Silva and Yakovenko [12] compared probability distributions of returns for three major stock-market indexes (Nasdaq, &P500 and Dow-Jones) with that given in Ref. [11] for the Heston model with stochastic variance; Silva, Prange and Yakovenko [13] investigated probability distributions of stock returns at mesoscopic time lags (return horizons) ranging from about a hour to a month; Remer and Mahnke [14] obtained the probability distribution of the logarithmic returns with empirical high-frequency data of DAX and its stocks; Vicente et al. [15] investigated the Heston model with stochastic volatility and exponential tails as a model for the typical price fluctuations of the Brazilian São Paulo Stock Exchange Index. Also, various modified Heston models have been proposed to fit the stock price and volatility. For example, Bonanno, Valenti and Spagnolo [16] considered an extension of the Heston model on the basis of a cubic nonlinearity for stock price and a correlation between two Wiener processes; Bonanno, Valenti and Spagnolo [17] studied statistical properties of the mean escape time of the returns in a market model which can be regarded as an extension of the Heston model; Valenti, Spagnolo and Bonanno [18–20] analyzed statistical properties of the hitting time distributions of stock price returns; Masoliver and Perelló [21,22] obtained the exact expression of survival probability which amounts to solving the complete escape problem and the mean exit time; Li and Mei [23,24] considered the effect of the delay time on the stability of a market model via a modified Heston model with a cubic nonlinearity and cross-correlated noise sources; Li and Mei [25] studied the stochastic resonance of stock prices in a finance system with the Heston model by introducing the extrinsic and intrinsic periodic information into the stochastic differential equations of the Heston model for the stock price. Accordingly, the Heston model is quite suitable for describing the stock price dynamics process.

The herd behavior is a natural phenomenon in a financial market. The crises of financial market **are sometimes originated** from the herd behavior of human beings [26]. Scharfstein and Stein [27] first found that some of the forces can lead to the herd behavior in investment. Afterwards, numerous studies on the herd behavior have been conducted, for instance, the herd behavior with the noise trader approach presented by Shleifer & Summers [28], a sequential decision model discussed by Banerjee [29], a model for stochastic formation of opinion clusters with the herd behavior proposed by Eguiluz & Zimmermann [30], the theory and evidence relating to the herd behavior reviewed by Hirshleifer & Hong Teoh [31], the herd behavior of daily data for 18 countries examined by Chiang & Zheng [32], the herd behavior on deal-of-the-day group-buying websites discussed by Liu & Sutanto [33], a new methodology to estimate the herd behavior in financial markets developed by Cipriani & Guarino [34], among others. Also, its dynamics and collective behaviors have attracted much attention among physical scientists. For example, Nirei [35] analyzed the self-organized criticality in a herd behavior model of financial markets; Zhao et al. [36] discussed the herd behavior based on self-serving agents in various kinds of complex adaptive systems; Huang [37] reviewed the herd behavior in experimental econophysics. Accordingly, the herd behavior is often considered as a tailor-made cause in explaining bubbles and crashes. Meanwhile, the bubbles and crashes of stock market can enhance the mean residence time in the positive or non-positive returns, respectively. In addition, the noise enhanced stability (NES) phenomenon is observed by the method of escape time and residence time. For example, Dubkov et al. [38] found the NES phenomenon in a piece-wise linear dichotomously fluctuating potential with metastable state; Mantegna and Spagnolo [39] investigated experimentally and numerically the probability distribution of residence times in periodically fluctuating metastable systems; Spagnolo, Dubkov and Agudov [40] discussed the overdamped motion of a Brownian particle in randomly switching piece-wise metastable linear potential; Yang et al. [41] analyzed the delay and NES; and Zeng et al. [42] observed the NES in an active Brownian motion and a model of lake approaching eutrophication. Also, the mean residence time and escape time are commonly used in pharmacology [43], biochemistry [44], an ecological system [45], a single-gene network [46], an energy depot model [47], physical chemistry [48], hydrologic systems [49], radiocarbon [50], medical science [51,52] and finance [53], among others. Therefore, the mean residence time is an appropriate measure for investigating the herd behavior.

The Heston model is here employed to describe the stock price dynamics. Then, we discuss theoretically and experimentally the herd behavior in a financial market via the method of the mean residence time. The rest of this paper is organized as follows. Section 2 investigates the problem of parameter estimation in a Heston model with the real financial data. Section 3 discusses statistical properties of stock price returns. Statistical inference on the herd behavior is given by the mean residence time in Section 4. A brief discussion is given in Section 5.

2. The Heston model and stock returns

To discuss the herd behavior in a financial market, we here adopt the Heston model to describe the dynamics of stock prices. Following Ref. [10], the Heston model can be defined as the following coupled Ito stochastic differential equations:

$$\begin{cases} \mathrm{d}r(t) = \left(\mu - \dfrac{\nu(t)}{2}\right)\mathrm{d}t + \sqrt{\nu(t)}\mathrm{d}\xi(t), \\ \mathrm{d}\nu(t) = a(b-\nu(t))\mathrm{d}t + c\sqrt{\nu(t)}\mathrm{d}\eta(t), \end{cases} \tag{1}$$

where $r(t) = S(t)/S(0)$, $\nu(t)$ denotes the volatility of stock price, μ is the drift parameter at macroeconomic scale, a is the mean reversion of the volatility $\nu(t)$, b is the long-run variance of $\nu(t)$, c is often called the *volatility of volatility*, i.e., it is the amplitude of the volatility fluctuation. The deterministic solution of the $\nu(t)$ process has an exponential transient with characteristic time being equal to a^{-1}, after which the process tends to its asymptotic value b [54]. Quantities $\xi(t)$ and $\eta(t)$