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Identification of speculative bubbles using state-space models with Markov-switching

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ABSTRACT

In this paper we use a state-space model with Markov-switching to detect speculative bubbles in stock-price data. To this end we express a present-value stock-price model in state-space form which we estimate using the Kalman filter. This procedure enables us to estimate a two-regime Markov-switching specification of the unobservable bubble process. The respective Markov-regimes represent two distinct phases in the bubble process, namely one in which the bubble survives and one in which it collapses. We ultimately identify bursting stock-price bubbles by statistically separating both Markov-regimes from each other. In an empirical analysis we apply our methodology to a plethora of artificial and real-world data sets. Our study has two major findings. First, we find significant Markov-switching structures in real-world stock-price bubbles. Second, in the stock markets considered our identification procedure correctly detects most speculative periods which have been classified as such by economic historians.

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1. Introduction

A classical belief is that under rational expectations and rational behaviour of economic agents any asset price should be in line with its market fundamental value. According to this view, economists often regard a persistent and substantial divergence between an asset price and its fundamental value as market irrationality. However, recent work elaborates that the dynamics of an asset price may well contain a self-fulfilling bubble component and that the explosive asset-price behaviour caused by the bubble may be consistent with rational behaviour among market participants.

Up to date, a multitude of theoretical studies examine the emergence of (stock-market) bubbles and their structural properties under rational expectations (e.g. Allen and Gale, 2000; Abreu and Brunnermeier, 2003). A closely related strand of literature is concerned with the econometric detection of speculative bubbles. We can roughly divide these papers into two groups. The first group of studies is based on so-called *indirect* bubble tests. Here, the authors apply sophisticated cointegration and unit-root tests to a dividend-price relationship and try to overcome the well-known econometric weaknesses of the standard tests. Most influential articles belonging to this category include Diba and Grossman (1988), Evans (1991) and several other contributions cited in McMillan (2007), Chen et al. (2009). The second group of studies, which are the more relevant to our paper, implement *direct* tests for speculative bubbles by explicitly formulating the existence of a bubble in the alternative hypothesis. Examples of such direct test procedures are West (1987), Wu (1997).

The key idea of West's (1987) direct bubble test is to compare two alternative estimators (i.e. an indirect and a direct estimator) for one particular parameter. More concretely, West constructs the indirect estimator from two different estimations, namely (1) from the estimation of the observable no-bubble Euler equation, and (2) from the estimation of a stationary autoregressive process which he assumes to govern dividends. West combines both estimations to obtain an indirect estimate of the linear relationship between dividends and stock prices. Alternatively, one can directly estimate the linear relationship between dividends and stock prices by performing a straightforward linear regression of stock prices on dividends. Under the null hypothesis of 'no bubble', the direct and the indirect estimates of the linear relationship should be equal (within the limits of statistical accuracy) while under the alternative of 'a rational bubble' both estimates should differ significantly from each other. Hence, the basic idea of West's (1987) test is to interpret a statistically significant difference between the direct and the indirect estimates as an indication of a speculative bubble. We may strengthen this interpretation further by additionally applying specification tests to the Euler

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equation and the autoregressive representation of dividends in order to rule out all model misspecification and leaving bubbles as the only possible source of the discrepancy between the two estimates.

Essentially, West's procedure tests the standard present-value model against an unspecified alternative which he interprets as an emergence from a speculative bubble. However, the test does not generate a time series of the bubble component. By contrast, Wu (1997), who also considers the deviation of stock prices from the present-value model, uses these discrepancies to construct a bubble time series. As in West (1987) he assumes that dividends follow an autoregressive process and treats the bubble as an unobservable variable which he estimates using the Kalman filter. In his empirical analysis Wu ascribes large portions of stock-price movements within the S&P 500 to speculative bubbles.

Another class of econometric models intensively used for the detection of bubble components are so-called Markov-switching (or regime-switching) models. These models try to capture discrete shifts in the generating process of time series data and were introduced by Hamilton (1989). Hall et al. (1999) add an important application of Markov-switching models to the bubble literature by treating each component of a simulated bubble process as a separate Markov-regime with constant transition probabilities between the regimes. Within a Monte Carlo experiment they analyze the power of Augmented-Dickey-Fuller unit-root tests with Markov-switching (Markov-switching ADF tests) and use these test procedures to detect bubble episodes. Although Vigfusson and Van Norden (1998) criticize this methodology on econometric grounds, Markov-switching approaches constitute a useful tool for modeling stock-market fluctuations and bubbles that switch between two or more states (e.g. Driffill and Sola, 1998; Brooks and Katsaris, 2005; Chen, 2009).

In this paper we treat the bubble as an unobservable variable as in Wu (1997) but extend his framework by allowing the bubble to switch between alternative regimes. Through this we aim at separating two distinct periods in the bubble process from each other, namely one in which the bubble survives and one in which it collapses. Technically speaking, we implement Markov-switching in our unobserved-components framework by adopting the methodology from Kim and Nelson (1999) who show how to use state-space models that are subject to regime-switching. Hitherto, this econometric technique has mainly been used for the detection of turning points in business-cycle research (see Chauvet, 1998 *inter alia*) and its application to the bubble literature constitutes the innovation of this paper.

In line with several previous studies from the bubble literature, we analyze both artificially generated bubble data as well as real-world data sets. The inclusion of artificial bubble processes has the advantage of knowing exactly when a bubble starts to evolve over time. Thus, we obtain precise information on the quality of our bubble-detection method. By contrast, the identification of bubble periods in real-world data sets turns out to be a more complicated matter. For this data type we are reliant on what economic historians classify *ex-post* as bubble periods. In our empirical analysis below we rely on the work of Kindleberger and Aliber (2005) who classify bubble periods in real-world stock-market data.

Our study has two major findings. First, we show that Markov-switching in the data-generating process of real-world stock-price bubbles appears to be a statistically significant phenomenon. Second, we obtain the encouraging overall result that our econometric framework is able to detect many bubble periods in our artificial data sets and is even more successful in tracking down real-world stock-price bubbles as classified by Kindleberger and Aliber (2005).

This paper contains six sections. Section 2 briefly reviews the basic present-value model. Section 3 transforms the present-value model into a state-space representation. We demonstrate how to estimate the state-space model including the unobserved asset-price bubble via the Kalman filter. In Section 4 we incorporate Markov-switching elements into the state-space model. Section 5 describes our artificial bubble processes, motivates the selection of our real-world data sets on the basis of historical bubble periods and presents the estimation results. Section 6 offers some concluding remarks.

2. Economic model

In this section we briefly review the standard present-value model of stock prices on the basis of the log-linear approximation as suggested by Campbell and Shiller (1988). For this, consider the following rational-expectations model of stock-price determination:

$$q = \kappa + \psi E_t(p_{t+1}) + (1-\psi)d_t - p_t, \tag{1}$$

where q is the required log gross return rate, $E_t(\cdot)$ is the mathematical expectation operator conditional on all information available at date t, $p_t \equiv \ln(P_t)$ is the log real stock price at date t, $d_t \equiv \ln(D_t)$ is the log real dividend paid at date t, and κ, ψ are parameters of linearization.

Eq. (1) constitutes a linear difference equation for the log stock price which we routinely solve by forward iteration. Imposing the transversality condition

$$\lim_{i\to\infty} \psi^i E_t(p_{t+i}) = 0,$$

we obtain the unique no-bubble solution (denoted by p_t^f) to Eq. (1):

$$p_t^f = \frac{\kappa - q}{1-\psi} + (1-\psi)\sum_{i=0}^{\infty} \psi^i E_t(d_{t+i}). \tag{2}$$

The no-bubble solution p_t^f in Eq. (2) represents the well-known present-value relation stating that the log stock price is equal to the present value of expected future log dividends. However, it is important to note that from a mathematical point of view the above transversality condition may not be satisfied. In that case, the no-bubble solution p_t^f represents only a particular solution to the difference equation (1), the general solution of which has the form

$$p_t = p_t^f + B_t, \tag{3}$$

with the process $\{B_t\}$ satisfying the homogeneous difference equation

$$E_t(B_{t+i}) = \frac{B_t}{\psi^i} \quad \text{for } i = 1, 2, \ldots \tag{4}$$

(e.g. Cuthbertson and Nitzsche, 2004, pp. 397–401).

Obviously, the general solution in Eq. (3) consists of two components. First, the no-bubble solution p_t^f only depends on log dividends and therefore represents the market-fundamental solution. Second, events extraneous to the market may drive the mathematical entity B_t which we therefore refer to as the rational speculative bubble component.

In order to circumvent nonstationarity problems, it is convenient to express the model in first-difference form which, by virtue of the Eqs. (2) and (3), is given by

$$\Delta p_t = \Delta p_t^f + \Delta B_t = (1-\psi)\sum_{i=0}^{\infty} \psi^i [E_t(d_{t+i}) - E_{t-1}(d_{t+i-1})] + \Delta B_t. \tag{5}$$

Following Wu (1997), we also assume that log dividends may contain a unit root but that we can approximate the dividend process $\{d_t\}$ by an autoregressive integrated moving average process. In particular, we assume an ARIMA$(h,1,0)$ process of the form

$$\Delta d_t = \mu + \sum_{j=1}^{h} \phi_j \Delta d_{t-j} + \delta_t, \tag{6}$$

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