

Derivation of Asset Price Equations Through Statistical Inference

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We develop a methodology to extract a quantitative model for behavioral effects in markets from empirical data. A set of 24 asset market experiments are utilized to derive an equation of price and its dependence on momentum, fundamental value, excess bid level and liquidity considerations. A difference equation is derived from a statistical analysis of the data. The methods are quite general and can be utilized in conjunction with other behavioral finance effects that influence price dynamics.

Introduction

The past two decades have provided a plethora of important examples of large financial bubbles, crashes and other market inefficiencies. Most prominent among these is the huge high-tech bubble of the late 1990s that culminated in the first quarter of 2000. The bubble and subsequent crash cost investors over six trillion dollars (Dreman [2001]) as investors bought into stocks with market values of billions despite a complete absence of historical earnings, and sometimes even revenue. Yet the prevailing wisdom at the time was that the market's assessment of value was reflected accurately in the price of the asset. This view was particularly common among ardent supporters of the efficient market hypothesis (EMH) and the stock underwriters and related analysts who profited from this viewpoint. During the same time period (1997–1999), however, a simple calculation of earnings potential, cash flow, etc., based upon even optimistic estimates, revealed a realistic price that was only a few percent of the trading prices of typical internet and high-tech stocks (Dreman [1999]). A similar analysis applies to other prominent bubbles such as the one in Japan during the 1980s that similarly displaced trillions of dollars worth of investments.

Academic economists often referred to such phenomena as “anomalies,” a term that suggests that EMH is a sound theory with a few minor quirks. These huge bubbles (and many in selected sectors) have changed the thinking of many, and have provided evidence that a fundamentally new approach beyond EMH is needed. In

particular, the behavioral effects are omnipresent in the market and need to be considered in terms of price adjustment.

In addition to the market phenomena discussed above, there has been a large body of economics experiments that have also cast doubt on the validity of EMH (Smith, Suchanek and Williams [1988], Porter and Smith [1994]) and references contained therein). In these experiments, participants trade an asset defined by the experimenter to have a specific payout (as we describe below for a particular case) and consequently have a well defined fundamental value. In hundreds of experiments, it has been observed that prices soar far above the fundamental value and subsequently crash.

Despite the empirical and laboratory evidence, EMH has an appeal that perhaps initially is difficult to comprehend. In the context of the laboratory experiments (and to some extent in the world markets) the salient feature may be described as follows. Once the asset is defined in a laboratory market, EMH provides a calculation for the trading price before the trading even begins. For example, if there is a particular dividend payout structure for an asset, then classical game theory implies that participants will not only optimize their choices in accordance, but will also assume that others will similarly engage in self-maximizing behavior. Hence, there is little reason to deviate from the calculated fundamental value according to EMH.

Based upon the unifying principles of classical game theory, EMH makes a set of precise predictions that are quantitative – even if they are often very inaccurate. In the absence of quantitative predictions based upon the growing literature of behavioral finance, the EMH would be the default theory for price adjustment.

In this paper we develop a methodology for utilizing experimental data to extract a quantitative model based upon postulated behavioral effects. This leads to a predictive model of price change that depends on features of the trading in addition to properties of the asset. In particular we consider the effects of momentum and excess bids in the context of a microeconomic framework

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that incorporates a finite supply of cash and asset. Momentum, or the tendency for rising prices to spur further buying, is a behavioral phenomenon that has complicated roots such as greed, avoiding regret, avoiding underperformance relative to peers, etc. The excess bids hypothesis (Smith, Suchanek and Williams [1988]) is the tendency for participants who can observe a diminishing of bids to be less likely to place bids themselves. Both of these concepts entail a shifting of supply and demand in response to the behavior of others rather than a change in the value of the asset. Other behavioral phenomena can be incorporated in a similar manner into the model we consider.

The result is an equation for the change in price based upon recent price trend, the relative cash per asset at the time, and the fraction of excess bids. In principle, this analysis can be applied to US markets in conjunction with a model for valuation.

Classical efficient market theory stipulates that the change in price per unit time depends on supply and demand (of the asset) which in turn depends only on price (but not on changes in price). This assumption alone provides a severe limitation that excludes many behavioral effects. In particular, this has the mathematical form of a first order ordinary differential equation which excludes the possibility of overshooting (prices crossing through the intrinsic value), prolonged under- or over-valuations and related phenomena. In other words, such observations in experimental asset markets (Smith, Suchanek and Williams [1988]) and stock markets (DeBondt and Thaler [1985]; Dreman [1998]) are incompatible with standard economic theory based upon this feature alone.

The basic microeconomic formalism of price change that depends upon supply and demand can be utilized with any number of behavioral effects by allowing supply and demand to depend upon other hypothesized effects. A statistical analysis can then determine whether there is support for these effects. This is the process we undertake in this paper for a large set of experimental data.

We utilize two sets of experiments in which subjects traded a single asset through a computer network during each of 15 periods (Caginalp, Porter and Smith, [2001]).

The Experiments

Participants are informed prior to the start of the experiment that each share of the asset pays a dividend (to the owner of the share during that period) with expectation value 24 cents at the end of each period (Davis and Holt [1993]). The single bid-offer auction mechanism yields a single price for each period. In other words, each participant can place orders to buy or sell any quantity of shares. At the end of the allotted time period, these orders are matched up so that each buy order above and

each sell order below the "trading price" is executed. Note that this requirement defines the "trading price" for the period. Each participant receives an endowment of cash and shares at the beginning of the experiment. The total initial cash distributed per participant varied from one experiment to another. In terms of dividends the experiments were of two types: (a) payment of dividends was made in cash at the end of each period and could be used during the remaining periods (dividends distributed), or, (b) payment of dividends was postponed until the end of the experiment (deferred dividends). These two features allow a statistical determination of the role of excess cash or liquidity. Also varied was the nature of the information provided to the participants in terms of trading information. In the closed book experiments, the participants see only their own trades and the resulting price and volume. In the open book experiments all trades (though not the identity of the traders) can be observed.

In particular, in the open book experiments, the traders can see when there are more sellers just above the asking price, and just a few bids at a high price. In this situation there is the possibility that traders react to the motivations of others. This in turn would provide a mechanism that reduces the bubble. The participants were undergraduates at the University of Arizona during 1999-2000 who had not previously participated in a similar asset market experiment. The data from one of the experiments is displayed in Figure 1 and Table 1(a).

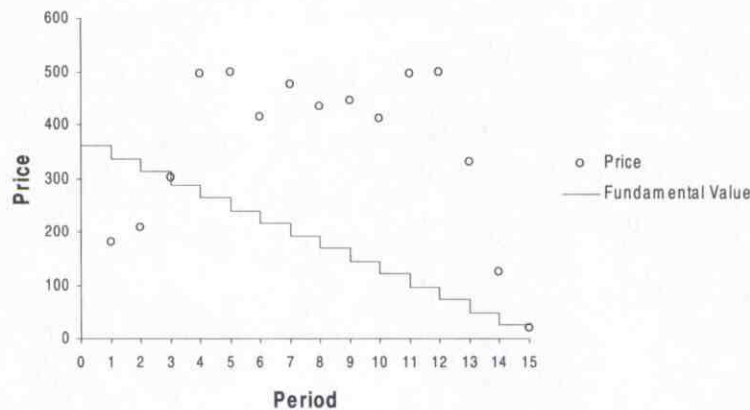
A mixed effects linear regression has been performed (Caginalp, Porter and Smith [2001]) for these experiments. Briefly, this is a statistical procedure that implements the linear regression by compensating for the fact that the data for the different periods of one experiment is generated by the same group. Without this adjustment the analysis would not be as convincing since the data of one period involves the same participants as the next, and is therefore not independent.

The analysis showed that the cash level was a significant factor in the trading prices in both the open and closed book experiments. For the closed book experiments the statistical analysis indicates that each dollar of additional cash per share raises the maximum trading price during the experiment by one dollar and the average price by 45 cents. Thus, these experiments confirm, contrary to expectations of rational markets theory, that the cash level is an important factor in price dynamics. The statistics provide somewhat weaker evidence for the hypothesis that an open book is associated with a more muted bubble. Our analysis below pursues this issue further.

The Price Equation

Our starting point is a basic price equation that states that the price change per unit time (with time

FIGURE 1
Typical Bubble Experiment (9/29/00)



Note: The solid line displays the fundamental value of the asset, namely the sum of the expected dividends. The circles show the actual trading prices for the experiment for each period. As is often the case, prices start low, then soar far above the fundamental value in a bubble, and then crash. In this experiment, traders were able to see the entire specialist array of bids and asks ("open book"). The cash level at the start of the experiment was double the value of the asset (i.e., \$7.20 in cash for every asset that is worth \$3.60 at the outset), and dividends were distributed each period, thereby augmenting the cash supply. The excess cash is a factor that inflates the bubble, while the open book has a slight dampening effect.

scale τ_0) is proportional to the excess demand divided by supply. In the discrete formalism of the experiments this is expressed as

$$\frac{\tau_0 [P(t+1) - P(t)]}{P(t)} = \frac{\text{Demand}(t) - \text{Supply}(t)}{\text{Supply}(t)}$$

Writing this equation in the continuum form allows us to express it as a differential equation

$$\tau_0 \frac{1}{P} \frac{dP}{dt} = \frac{D - S}{S}$$

where S and D are supply and demand. This form has the advantage that a large amount of theory is available for deducing key properties of solutions. In particular, if the right hand side depends only on P itself (and not on dP/dt , i.e., the change in P) then the solution $P(t)$ cannot exhibit oscillations or overshooting about a constant value. In other words once the "equilibrium price" is reached; the solution cannot move past it and must evolve gradually toward it. However, if supply and demand depend upon a price change history, i.e., the trend, basic theory indicates that solutions can overshoot and oscillate in the same way that a pendulum oscillates about the equilibrium point (with or without damping). We start with the price equation above, and proceed to define the supply and demand.

In a system with one asset (in addition to cash) we let B denote the fraction of the total wealth in the asset, so that $1-B$ is the fraction in cash. The demand, D , is then $k(1-B)$ where k is the transition rate, or the proba-

bility that a unit of cash will be used to bid for the asset at the prevailing price. In other words, if there are a large number of traders with equal amounts of cash, then k defines the fraction of traders who will submit buy orders. Similarly, one has $S = (1-k)B$. For a system with $N(t)$ shares and $M(t)$ cash one has the identities (Caginalp and Balenovich [1999]),

$$B = \frac{NP}{NP + M}, \quad 1 - B = \frac{M}{NP + M}, \quad \frac{1 - B}{B} = \frac{M}{NP},$$

so that the price equation above can be written as

$$\tau_0 \frac{dP}{dt} = \frac{k}{1-k} \frac{M}{N} - P.$$

In discrete form this can be written as

$$P(t+1) = \frac{1}{\tau_0} \frac{k}{1-k} \frac{M(t)}{N} + \left(1 - \frac{1}{\tau_0}\right) P(t)$$

Our central objective is to estimate statistically, from the experimental price data for each period, the quotient of the transition probabilities in and out of the stock, $\kappa = k(1-k)^{-1}$. Unlike previous works we do not hypothesize a particular form for this crucial variable, κ . We examine the data and allow the statistics to select the relevant terms and their magnitude. The independent variables will include the price trend, the discount from fundamental value, the excess bids at the end of the period and the difference between the trading price and the "liquidity value" defined below.

Table 1. Data for Experiments

Period	Price	Fundamental Value	Number of Shares	Money Supply	Excess Bids	Liquidity	Relative Value	Relative Price	Relative Liquidity
Table 1(a) (09/29/00)									
1	180	360	20	14,400	63	720	0.5	—	0.75
2	208	336	20	14,560	37	728	0.380952	0.155556	0.714286
3	302	312	20	14,720	28	736	0.032051	0.451923	0.589674
4	496	288	20	15,280	17	764	-0.72222	0.642384	0.350785
5	500	264	20	15,440	39	772	-0.89394	0.008065	0.352332
6	415	240	20	16,000	15	800	-0.72917	-0.17	0.48125
7	476	216	20	16,160	0	808	-1.2037	0.146988	0.410891
8	435	192	20	16,160	8	808	-1.26563	-0.08613	0.461634
9	446	168	20	16,720	7	836	-1.65476	0.025287	0.466507
10	411	144	20	16,720	1	836	-1.85417	-0.07848	0.508373
11	497	120	20	17,920	-6	896	-3.14167	0.209246	0.445313
12	498	96	20	18,480	-6	924	-4.1875	0.002012	0.461039
13	330	72	20	19,680	-6	984	-3.58333	-0.33735	0.664634
14	125	48	20	20,880	-10	1044	-1.60417	-0.62121	0.880268
15	21	24	20	21,440	174	1072	0.125	-0.832	0.98041
Table 1(b) (03/06/00)									
1	60	360	36	6,480	61	180	0.833333	—	0.666667
2	80	336	36	6,768	32	188	0.761905	0.333333	0.574468
3	110	312	36	7,056	30	196	0.647436	0.375	0.438776
4	146	288	36	8,064	75	224	0.493056	0.327273	0.348214
5	210	264	36	8,352	32	232	0.204545	0.438356	0.094828
6	250	240	36	9,360	-1	260	-0.04167	0.190476	0.038462
7	248	216	36	9,648	-3	268	-0.14815	-0.008	0.074627
8	239	192	36	9,648	6	268	-0.24479	-0.03629	0.108209
9	230	168	36	10,656	-3	296	-0.36905	-0.03766	0.222973
10	220	144	36	10,656	1	296	-0.52778	-0.04348	0.256757
11	210	120	36	12,816	16	356	-0.75	-0.04545	0.410112
12	195	96	36	13,824	14	384	-1.03125	-0.07143	0.492188
13	150	72	36	15,984	79	444	-1.08333	-0.23077	0.662162
14	20	48	36	18,144	95	504	0.583333	-0.86667	0.960317
15	26	24	36	19,152	266	532	-0.08333	0.3	0.951128
Table 1(c) (04/28/00)									
1	100	360	20	14,400	132	720	0.722222	—	0.861111
2	130	336	20	14,560	70	728	0.613095	0.3	0.821429
3	150	312	20	14,720	57	736	0.519231	0.153846	0.796196
4	201	288	20	15,280	94	764	0.302083	0.34	0.736911
5	352	264	20	15,440	45	772	-0.33333	0.751244	0.544041
6	240	240	20	16,000	43	800	0	-0.31818	0.7
7	302	216	20	16,160	26	808	-0.39815	0.258333	0.626238
8	309	192	20	16,160	23	808	-0.60938	0.023179	0.617574
9	302	168	20	16,720	34	836	-0.79762	-0.02265	0.638756
10	375	144	20	16,720	19	836	-1.60417	0.241722	0.551435
11	315	120	20	17,920	59	896	-1.625	-0.16	0.648438
12	314	96	20	18,480	30	924	-2.27083	-0.00317	0.660173
13	352	72	20	19,680	29	984	-3.88889	0.121019	0.642276
14	275	48	20	20,880	18	1044	-4.72917	-0.21875	0.73659
15	175	24	20	21,440	-1	1072	-6.29167	-0.36364	0.836754

Note: Table 1(a) shows the data for Figures 1 and 2, while Tables 1(b) and (c) show the data for Figures 3 and 4, respectively. For each of the experiments, the tables display the trading price for the period (column 2) and the fundamental value (column 3). In column 5, the money supply for each period is displayed. This is the sum of the endowed cash plus the dividends distributed which varies depending on the random draw for that period. Column 7 shows the cash per share during each period. Column 6 shows the number of bids minus the number of asks, resulting in the excess bids that are not fulfilled during the period. A negative number means there were more attempts to sell than buy. Columns 8, 9 and 10 display the data for the parts of the price equation (before the "Results of Statistical Analysis").

The independent variable representing the price trend is simply the relative difference between the current price and the prior period price. The discount from fundamental value is expressed as the relative difference in the expected value of remaining dividends,

$V(t)$, and the price. Smith, Suchanek and Williams [1988] hypothesized and found some support for the assertion that an indicator of short term price movement would be the number of bids that were not accepted (i.e., excess bids). Accordingly, we use as one

of our independent terms the difference between the bids and asks in the form $EX = (\text{Bids}-\text{Asks})$.

The price equation above for this closed system has already incorporated the relative amount of cash, i.e., $1 - B$. As noted in earlier studies (Caginalp and Balenovich [1999]) there is an additional quantity with units of price per share, beyond $P(t)$ and $V(t)$. This is the liquidity value, $L(t) = M(t) / N(t)$ which emerges from the equations in a natural way, measuring the cash supply per share. The price equation has already been formulated to incorporate the effect of the cash supply (since it is written in terms of the fraction of wealth in asset versus cash). The question to be determined statistically is whether there is additional (for example nonlinear) dependence on this term. Hence we examine also whether the relative difference between the price and this liquidity value, $L(t)$, influences the dependent variable, κ . In summary, we would like to understand the dependence of κ on these independent variables in the form below:

$$\kappa = \alpha_1 \frac{P(t) - P(t-1)}{P(t-1)} + \alpha_2 \frac{V(t) - P(t)}{V(t)} + \alpha_3 EX + \alpha_4 \frac{[M(t)/N] - P(t)}{M(t)/N}$$

If the equation has already incorporated liquidity (or excess cash) fully, the coefficient α_4 should be zero. Utilizing the previous equation for κ presents a complication in that τ_0 is not determined. Consequently, we use a procedure that will evaluate this parameter along with the others simultaneously.

We substitute this last equation for κ into the discrete price equation to obtain

$$P(t+1)/P(t) = \gamma_1 \frac{P(t) - P(t-1)}{P(t-1)} \frac{M(t)}{NP(t)} + \gamma_2 \frac{V(t) - P(t)}{V(t)} \frac{M(t)}{NP(t)} + \gamma_3 EX \frac{M(t)}{NP(t)} + \gamma_4 \frac{[M(t)/N] - P(t)}{M(t)/N} \frac{M(t)}{NP(t)} + \gamma_0$$

The magnitudes and the statistical significance of the coefficients will then indicate the particular form of

the price equation. The α_i are subsequently obtained from the γ_i by first using $\gamma_0 = 1 - \frac{1}{\tau_0}$ to determine τ_0 , yielding $\gamma_i = \frac{\alpha_i}{\tau_0}$, for $i = 1, 2, 3, 4$.

Results of Statistical Analysis

We consider separately the two sets of experiments defined above as closed book and open book. Using the "mixed effects" model (described above) in the Splus software, we estimate the coefficients $\gamma_0, \gamma_1, \gamma_2, \gamma_3$ and γ_4 . Note that the money supply must also be updated for each period due to the distribution of dividends in some of the experiments. Proceeding first with the closed book experiments, we list in Table 2 the values and the statistical significance of the coefficients.

The statistics indicate that the coefficients for the relative price change (momentum), γ_1 , and the relative discount from valuation, γ_2 , are both positive and statistically highly significant, with t-values exceeding 3 and 9, respectively. This procedure thereby establishes the relevance of these terms, and yields a quantitative measure of the importance of these terms to the traders. The excess bids coefficient, γ_3 , is orders of magnitude smaller and of borderline statistical significance in these closed book experiments. Finally, we recall that the coefficient for liquidity, γ_4 , is important in terms of understanding whether the liquidity (or excess cash) has been incorporated properly. The data indicate that the coefficient is well within the error for zero. This provides good confirmation that the basic model incorporates the effect of excess cash accurately.

We perform the mixed effects linear regression for the open book experiments (See Table 3) and similarly evaluate the coefficients γ_i . The results are similar in terms of the momentum, valuation and liquidity. The excess bids coefficient, however, is now 0.001 with a t-value of 4.03 with $p=0.0001$, and is thus very significant, unlike the closed book case. It appears that the information provided by the open book has the effect of focusing attention on the actions of other traders and their order placement. If the effect of excess bids were significant for the closed book case, the natural explanation would be that traders whose bids were not accepted are making similar bids in the next period, thereby boosting

Table 2. Closed Book Experiments

Coefficient	Value	Std. Error	df	t-value	p-value
γ_0 (constant)	1.056512	0.03079739	164	34.30526	<.0001
γ_1 (trend)	0.0503404	0.01610477	164	3.12353	0.0021
γ_2 (value)	0.058747	0.0060241	164	9.75207	<.0001
γ_3 (excess bid)	0.000052	0.00003667	164	1.42884	0.155
γ_4 (residual liquidity)	-0.003312	0.01474023	164	-0.22467	0.8225

Note: In this set of experiments, traders did not have access to the bid-ask book. There are 182 observations and 14 groups. The results show that there is a high statistical significance associated with both the trend and the valuation terms.

Table 3. *Open Book Experiments*

Coefficient	Value	Std. Error	df	t-value	p-value
γ_0 (constant)	0.9799765	0.08855180	116	11.06670	<.0001
γ_1 (trend)	0.0604199	0.03648699	116	1.65593	0.1004
γ_2 (value)	0.0305242	0.00749208	116	4.07420	0.0001
γ_3 (excess bid)	0.0010647	0.00026383	116	4.03542	0.0001
γ_4 (residual liquidity)	0.0005084	0.02989202	116	-0.01701	0.9865

Note: These experiments featured an open specialists book that enabled traders to see all other bids and asks (though not the identities of the traders). There were 130 observations and 10 groups. The coefficients of the trend and valuation terms are again statistically significant. Unlike the closed book experiments there is a high degree of statistical significance to the excess bids coefficient, suggesting that traders utilize this information on the strategies of other traders. In both sets of experiments, the residual liquidity term (γ) is statistically insignificant, suggesting that the liquidity issues have been incorporated adequately in the model.

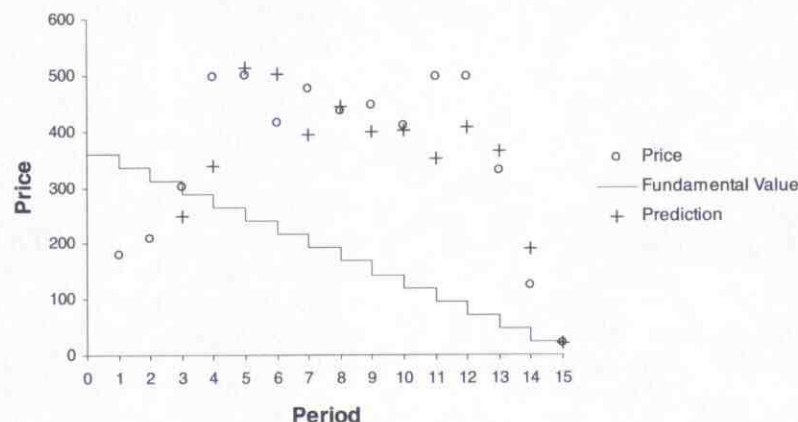
prices. The fact that the excess bids hypothesis is significant only when there is an open book suggests that the effect is a consequence of observing the actions of other traders. This provides some additional evidence that traders are influenced directly by the behavior of others and try to anticipate future actions. The price equation is thereby completed with the values of α_i and τ_0 obtained from the relations above. The price equation thereby generates predictions for the subsequent period, starting with period three. The results for three typical experiments are displayed in Figures 2, 3 and 4, and in Table 1.

Conclusion

We have described a procedure for deriving a difference equation deductively from a very general form of a

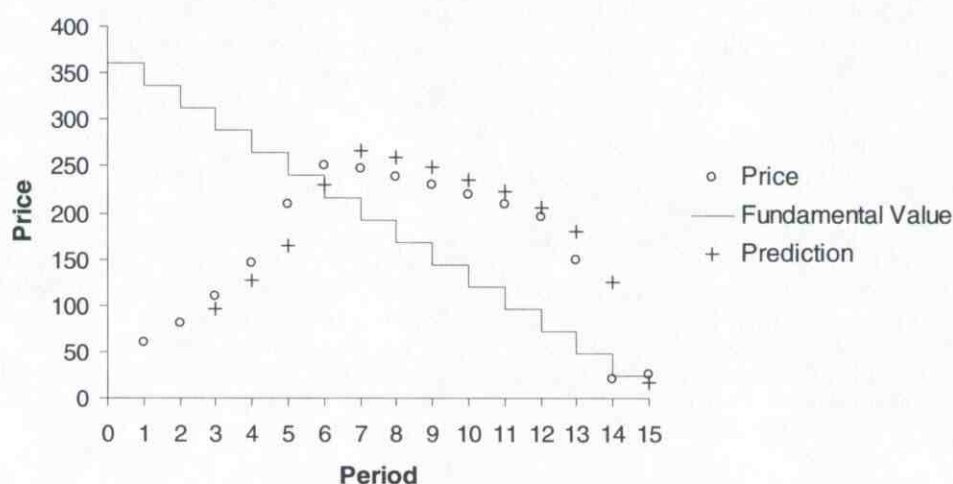
price equation. The price equation simply expresses the conservation of cash and the principle that prices move in relation to supply and demand. The approach we have used has an advantage over a purely statistical approach since the basic conservation laws reduce the degrees of freedom and facilitate estimation of parameters. This methodology has the potential for the testing of many different hypotheses and possibilities. We have examined the effects of momentum, or recent price trend, the discount from true value, and the effect of excess bids. Additional behavioral hypotheses can be examined in conjunction with those we have tested. The coefficient of zero (within statistical error) for γ_4 confirms this conclusion. In other words, if the modeling of the conservation of cash and the dependence of price on supply and demand had been done inadequately, this coefficient would have been either positive (indicating more than

FIGURE 2
Experiment of Figure 1 Superimposed With Predictions From Our Equations



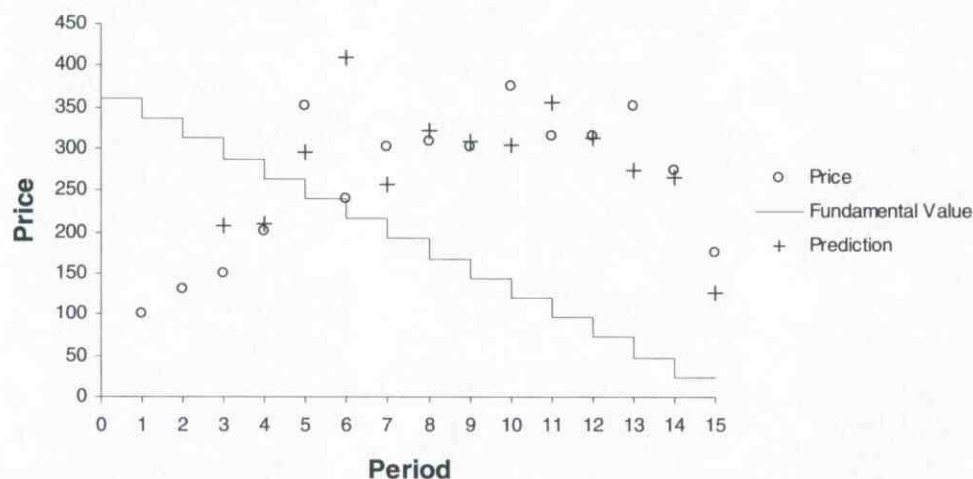
Note: The plus signs (+) indicate the period-by-period forecasts made by our model that is derived from the entire set of ten open book experiments, and based upon price momentum, excess bids and the finiteness of cash, in addition to valuation. Due to the differencing scheme, the predictions do not begin until period three. Early in the experiment prices soar due to the momentum factor, even though trading prices are above fundamental value. Note, however, that the prediction for period six is not a further increase in price, as would be suggested simply by pure momentum. This is due to the extreme deviation from fundamental value in relation to the available cash. Hence, the model correctly forecasts a turn in the market, though the actual drop is even larger. In period ten a lower forecast is made due to a diminishing of the excess bids (leading traders to believe that the aggressive bidding may have tapered off), and a dividend draw that was zero (so that there is no additional cash to fuel the bubble). However, the actual trading price for period eleven is in fact higher, perhaps due to the momentum of the prior periods. Nevertheless, prices stall in the following period and collapse during periods thirteen to fifteen.

FIGURE 3
Experiment with low cash levels (03/06/00)



Note: In this closed book experiment (i.e., traders cannot see others' bids or asks) the cash level was one-half of the asset level. In other words, there is one-fourth of the cash supply of the experiment shown in Figures 1 and 2. Dividends are also distributed (rather than deferred) in this experiment. Once again, the price momentum is predictably responsible for the rise in the early periods. As prices move above fundamental value, the cash supply is inadequate (even with the additional cash from the dividends) to fuel a large bubble, as the model correctly predicts.

FIGURE 4
Another open book experiment with high cash level (04/28/00)



Note: This experiment is performed under the same conditions of the experiment shown in Figures 1 and 2. The largest deviations from the predictions occur in periods six and thirteen, when the effects of momentum are smaller than predicted by the model.

proportional dependence on the cash supply) or negative (indicating that there is less than proportional dependence on the cash supply).

This methodology also offers the possibility of comparing data from different experimental procedures and quantitatively linking experimental data with field data. In particular, the coefficients obtained in this study can be compared with other experiments to test for the robustness of the statistical significance as well as the range of these parameters among different groups of traders. A resolution of these issues would help determine the degree of universality in the behavioral concepts. As new effects are determined, additional terms

will appear in the transition function (defined above) thereby developing the paradigm of behavioral finance from the perspective of asset price dynamics.

The application of these methods to field markets requires a model of valuation and some method of estimating the cash level in the system. The latter is the more difficult as it presumably needs to be estimated based upon optimization utilizing recent price data. Alternatively, if one makes the assumption that the key parameters (α_i , τ_0) are identical to those of experiments, then the methods could be useful in terms of estimating the cash flow into the market that would help predict future direction.

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