Sunspots in the Laboratory
John Duffy; Eric O'N Fisher
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By JOHN DUFFY AND ERIC O'N. FISHER*

We show that extrinsic or nonfundamental uncertainty influences markets in a controlled environment. This work provides the first direct evidence of sunspot equilibria. These equilibria require a common understanding of the semantics of the sunspot variable, and they appear to be sensitive to the flow of information. Sunspots always occur in a closed-book call market, but they happen only occasionally in a double auction, where inframarginal bids and offers are observable. (*JEL* C9, D5, E3)

The effects of extrinsic uncertainty have fascinated social scientists since well before Charles Mackay (1841). Is there some kind of randomness, having nothing to do with fundamentals, that nevertheless serves as a way of coordinating the expectations and consequent plans of market participants? This question has received sound theoretical foundations in David Cass and Karl Shell (1983) and Costas Azariadis (1981), and it has spawned a vast literature on "sunspot" equilibria in macroeconomics, finance, and other fields.[1]

Despite the extensive theoretical attention that has been paid to sunspot equilibria, there is little *direct* evidence that extrinsic uncertainty is responsible for any of the volatility observed in actual markets.[2] The difficulty lies in identifying sunspot variables and isolating their effects from those of fundamentals. A possible resolution is to examine a controlled environment where sunspot variables can be separated from shocks to preferences or endowments. In this paper, we describe such an experiment.

We examine an environment with a single good and two stable equilibria. Subjects are buyers or sellers, and prices are determined in a call market or in a double auction. The sunspot variable consists of random announcements about market conditions. This random variable has no bearing on the fundamentals, but buyers and sellers can use it as a coordination device.

The experiment has yielded three important findings. First, we provide *direct* evidence—the first ever—of sunspot equilibria. Second, we show that institutions matter by demonstrating that the market mechanism—call market or double auction—is an important determinant of whether sunspot equilibria are likely to occur. Third, we show that the semantics of the sunspot variable are important; a common understanding of the meaning of a sunspot realization

* Duffy: Department of Economics, University of Pittsburgh, 4901 Posvar Hall, 230 South Bouquet Street, Pittsburgh, PA 15260 (e-mail: jduffy@pitt.edu); Fisher: Department of Economics, The Ohio State University, 410 Arps Hall, 1945 North High Street, Columbus, OH 43210 and Federal Reserve Bank of Cleveland (e-mail: fisher.244@osu.edu). The authors gratefully acknowledge funding from the National Science Foundation under grants SES-0111123 and SES-0111315. They also thank Tim Cason, Jack Ochs, two anonymous referees, and seminar participants at the Economic Science Association Meetings, the SUNY Stony Brook Summer Game Theory Festival, Boston College, Case Western Reserve University, Carnegie-Mellon University, the University of Iowa, Oberlin College, Queen's University Belfast, the University of Warwick, and the Federal Reserve Bank of Cleveland for helpful comments on earlier drafts.

[1] Roger E. A. Farmer (1999) gives a very good summary of the importance of these ideas in macroeconomics. William S. Jevons (1884) used the term "sunspot" because he mistakenly believed that solar activity drove the business cycle. In the modern parlance, a sunspot is any random variable that is unrelated to fundamental factors, like endowments, preferences, or technology.

[2] There is quite a lot of indirect evidence using calibrated general equilibrium business cycle models, which exploit the possibility that the set of equilibria in such models may be indeterminate. This indeterminacy allows arbitrary self-fulfilling beliefs to become an additional source of volatility. See Jess Benhabib and Farmer (1999) for a survey of this literature. We regard this as indirect evidence since the sunspot variables and the coordination processes are not identified.

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appears necessary for sunspot equilibria to obtain.

Sunspot equilibria occur reliably only in a closed-book call market, with its centralized determination of price. They happen less often in the double auction, where many different bids, offers, and transaction prices may be observed. This difference has to do with the flow of information under the two mechanisms and with how agents learn to believe in the efficacy of using the sunspot as a coordinating device. In the closed-book call market, the market-clearing price is the only feedback that subjects receive. Since market participants cannot communicate, the sunspot variable plays a critical role in coordinating actions. In the double auction, the best bids and offers are always visible, and they are being updated almost continuously. Further, the different prices at which transactions occur within a period give information that may reinforce or obfuscate the meaning of the sunspot variable. Thus, in the double auction, individuals communicate indirectly and may not need to condition their actions on a public sunspot variable.

An important implication of our findings is that theorists ought to pay more attention to information flow in future extensions of sunspot theory. Furthermore, theories relying on extrinsic uncertainty ought to make explicit how people interpret sunspot variables. Learning to believe in sunspots is a lot like learning a language of the market; it is essentially a social phenomenon, and the salience of a potential sunspot variable depends upon a shared common culture of the market.

I. Related Literature

We are not the first to use the laboratory to try to obtain direct evidence of sunspot equilibria. Ramon Marimon et al. (1993) designed an experiment based on an economy with overlapping generations where sunspots might play a role. Their environment had two steady-state perfect foresight equilibria and one where prices followed a two-period cycle. This multiplicity allowed for the possibility that prices might depend upon a sunspot variable.

Those authors placed a blinking square that cycled between red and yellow on subjects' computer screens in an effort to coordinate expectations on the cyclical equilibrium. Without any correlation between sunspot realizations and actual price movements, subjects ignored the different colors of the blinking square—the sunspot variable—and coordinated on one of the steady states. So the authors tried to induce a correlation between price movements and sunspot realizations by alternating the number of subjects playing the role of "young" agents in each period of the training phase. This design amounted to an endowment shock that was perfectly correlated with realizations of the sunspot variable; it induced a cycle in prices in the experiment's training phase. Once this phase was over, the shock to economic fundamentals was eliminated. Afterward, the subjects usually coordinated near one of the steady-state equilibria. In the sessions where prices remained volatile after the initial training phase, the actual price path deviated substantially from the predicted sunspot equilibrium. Thus, while Marimon et al. (1993) made a significant effort to get subjects to condition their expectations on a sunspot variable, they did not observe a sunspot equilibrium in any of their five sessions.

Our experimental design differs considerably from theirs. Sunspot equilibria in macroeconomics are often modeled in dynamic general equilibrium environments that are difficult to implement in the laboratory. This consideration led us to use treatments based on two certainty equilibria in an economy without asset markets.[3] Indeed, one should think of our design as corresponding to the simplest case that Cass and Shell (1983) studied: a randomization over certainty equilibria.

In most of our treatments, the sunspot variable is a random, public announcement as to whether a high or a low price is likely to occur. The announcement serves as a coordination device that subjects are free to use or to ignore. Our sunspot variable provides the social and cultural context that was missing from Marimon et al.'s (1993) blinking square. Indeed, an important implication of our work is that *the*

[3] As Azariadis and Roger Guesnerie (1986, p. 726) observe, "Sunspot phenomena, of course, are not necessarily dynamical; the related concept of 'correlated equilibrium' does not require the passage of time."

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semantics of the language of sunspots matters; if it is not immediately clear to everyone how a sunspot variable is to be interpreted, then it is unlikely to play any role in coordinating expectations. Common knowledge about the sunspot variable also appears to be important. So a public announcement that everyone understands is a good candidate for a sunspot variable. While our announcement may seem context laden, it remains a genuine sunspot variable, since it has nothing to do with economic fundamentals.[4]

We think that our framework is the simplest one in which to observe a sunspot equilibrium; the equilibrium involves randomization over two certainty equilibria in an economy in which there are no assets at all. Thus asset markets are entirely incomplete, and the only important dynamic in our framework is whether the subjects learn to believe in the sunspot as the experimental session evolves. We use a very stringent criterion for judging whether sunspots matter: we say that a sunspot equilibrium obtains only if subjects coordinate on the random announcement in every period, beginning from the very first period. Subjects must start off believing in the sunspot, and their beliefs must always be self-fulfilling. We say that a sunspot equilibrium fails to obtain when subjects do not follow the sunspot announcement in one or more of the ten periods of a session.

There is some related experimental work on two-person games with multiple equilibria where subjects respond to recommendations made by the experimenter.[5] While the aim of this literature is different from ours, one interesting finding is that pairs of subjects will follow a recommendation to play a strategy that is not dominated, as long as it does not result in asymmetric payoffs. By contrast, we observe that large groups of subjects are willing to coordinate on our announcements unerringly and immediately, even though some subjects strictly prefer one equilibrium over the other. This finding may occur because each subject has less influence in a market than in a two-person game.

There is an experimental literature that considers whether asset markets can be manipulated (e.g., Colin F. Camerer, 1998) or whether such markets are susceptible to price bubbles and crashes (e.g., Vernon L. Smith et al., 1988, and Vivian Lei et al., 2001). While this literature is similar in spirit to our experiment, the notion of a sunspot equilibrium is quite distinct from that of a price bubble. Among other differences, stationary sunspot equilibria are of indefinite duration, whereas most price bubbles eventually burst. Further, in those experiments, price bubbles are not equilibrium phenomena. Still, we view this literature as being complementary to our paper.

There is also an experimental literature in social psychology on *self-fulfilling prophecies* beginning with Robert Rosenthal and Lenore Jacobson's seminal (1968) study demonstrating how teachers' false expectations about their students' abilities shaped the students' subsequent performance. This strand of research differs in many respects from the sunspot literature in economics. Psychologists define self-fulfilling prophecies as false beliefs that are nevertheless fulfilled, whereas economists are agnostic about the verity of nonfundamental beliefs. Psychologists focus on the "expectancy effects" of individuals, whereas economists are concerned with the "madness" of crowds. Experimental psychologists typically do not offer their subjects salient monetary incentives and sometimes use deception to induce false beliefs; teachers in Rosenthal and Jacobson's study were told that some of their students had "unusual potential for intellectual growth," even though this claim was spurious. In contrast, we did not practice any kind of deception and were quite explicit about how subjects' choices translated into monetary rewards.

Finally, we note that there is a relationship between our sunspot equilibria and the notion of

[4] Indeed, Farmer (1999, p. 225) suggests a very similar example of a context-laden sunspot. He states, "I like to think of the sunspot as the predictions for the economy of the *Wall Street Journal.*"

[5] See, for example, Jordi Brandts and Charles A. Holt (1992); Brandts and W. Bentley MacLeod (1995); John B. Van Huyck et al. (1992). Andrew Schotter (2003) and associates examine how subjects play games when they receive advice from other subjects. Hakan Holm (2000) examines how announcements of an opponent's gender affect play in coordination games. Colin F. Camerer and Marc Knez (1997) examine the effect of announcing bonus payments to groups of subjects who all choose the same action in a "weak-link" coordination game.

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a *correlated equilibrium*.[6] Our sunspot variable provides a common signal about which certainty equilibrium will actually occur, and each subject takes an action conditional upon it. Unilateral deviations are unprofitable, and the sunspot equilibrium is a correlated equilibrium of a simple game. Since there are no previous experimental tests of this concept, our results are of independent interest to game theorists.

II. Hypotheses

We explore three fundamental hypotheses. The first is:

HYPOTHESIS 1: *Sunspot equilibria exist. Further, they can be easily replicated.*

While the logical foundations of equilibrium theory based upon endogenous expectations of extrinsic uncertainty are quite well founded, the econometric evidence from field data is mixed at best. Indeed, Robert P. Flood and Peter M. Garber's seminal work (1980) showed how difficult it is to find price bubbles using econometric tests based upon a well-specified model. Hence, there is compelling need for evidence from the laboratory. As we show below, when there is a clear semantic mapping from sunspot variable realizations to actions, a sunspot equilibrium always occurs in the call market and often happens in the double auction. Our findings suggest that sunspot equilibria in call markets are easily replicated; others will now be able to build upon our design.

Our second hypothesis is subtler, and it is perhaps of greatest interest to both economic theorists and policymakers.

HYPOTHESIS 2: *Sunspot equilibria are sensitive to the flow of information.*

The usual Walrasian framework that serves as the foundation for any theory of extrinsic uncertainty is based upon a static notion of the flow of information. It actually obviates an important element of many field markets, where there is nearly continuous trading between events that signal the advent of important new information. The simplest way to allow for a differential flow of information in asset markets in the laboratory is to highlight the difference between a double auction, in which several transactions can occur in a period, and a call market, in which only one price clears the market in each period. Of course, in a double auction, all the inframarginal bids and offers become a part of the information set of every trader as the period unfolds, while only one price becomes public knowledge in a call market, once the price fixing has occurred.

Our third hypothesis may be of interest to both philosophers and social scientists.

HYPOTHESIS 3: *The semantics of the sunspot variable matter.*

When we speak of semantics, we have three things in mind. First, a sunspot variable can be a coordinating device only if its meaning is transparent. Second, a sunspot variable must have realizations that are public; thus it is common knowledge that everyone in the market sees the same random variable, and you and I believe that everyone else ascribes the same meaning to it that we each do. Third, there must be some "training period" during which we all come to believe that the sunspot variable is actually correlated with market outcomes. In brief, learning to believe in sunspots has many of the same elements as learning a language. Seeing a group of children playing soccer, Ludwig Wittgenstein (1953) is alleged to have had the remarkable insight that language is actually a game that serves a useful social function only if everyone has a shared sense of its conventions. Hypothesis 3 states that a sunspot variable will serve as a coordinating device if it is easy to understand and a useful guide for one's decisions.[7]

[6] See Robert J. Aumann (1974) for the definition of correlated equilibrium, and James Peck and Karl Shell (1991) on the relationship between correlated and sunspot equilibria.

[7] David K. Lewis (1969) might think of our sunspot variable as a convention of truthfulness. Suppose that the sunspot variable is "the forecast is high." Then each agent may well take an action (like deciding to bid or offer at a high price) that in the aggregate will lead to a high-priced equilibrium. Each buyer or seller does so because he or she thinks that others will do the same, and the community has a common interest in achieving maximal ex post economic

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TABLE 1—EXPERIMENTAL DESIGN

		Announcements	
		Predetermined by experimenter	Public coin flips
Market mechanism	Double auction	Cell 1 4 Sessions	Cell 2 5 Sessions
	Call market	Cell 3 3 Sessions	Cell 4 3 Sessions
Sunspot semantics	Call market with "sunshine" and "rain" announcements	Cell 5 3 Sessions	

III. Experimental Design

For most of our research, we used a 2 × 2 design where the treatment variables were the *market mechanism* and the *forecast announcement.*[8] The two different market mechanisms were a double auction and a call market.[9] There were two kinds of random forecast announcements: an opaque one where realizations of the sunspot variable had been determined in advance and a transparent one where a coin was flipped publicly each period. The four cells of the main design are presented in Table 1.

We used an extremely simple market design with two different demand and supply curves that intersected near a price of 100 or a price of 200. In either case the equilibrium quantity was six. The instructions told the subjects that their marginal costs and valuations depended upon the end-of-period median price, and this statistic was determined solely by their actions during the trading period. Suppliers made money by selling above their marginal costs and buyers made money by purchasing below their marginal valuations. At first blush, it may seem unusual that costs and valuations "depend upon" a statistic based upon transactions prices, but this formulation is just a reduced form for an economy with multiple equilibria.[10] Of course, there is no fundamental uncertainty because no one's payoffs actually depend on any random variable. In this framework, an equilibrium price is just one that clears the market, given that it is anticipated correctly.

Figure 1 shows the actual demand and supply curves that were used in all sessions. The steps indicate precisely which valuations and costs accrue to which subjects. The five buyers in Figure 1 are labeled B1 through B5 and the five sellers are labeled S1 through S5. Notice that each subject has two valuations or costs along a given (price-contingent) demand or supply curve; they correspond to the two units he or she could trade. Buyers were told that their profits were the difference between their valuation and the price they paid for a unit, while sellers were instructed that their profits were the difference between their sales price and the cost of that unit. Figure 1 reveals that there is a continuum of equilib-

surplus. Lewis argues that this "convention of truthfulness" is the essence of language as a social norm.

8 We urge the interested reader to retrieve the instructions for any treatment at http://economics.sbs.ohio-state.edu/efisher/duffyfisher/docs. The files are named cell1.PDF, cell2.PDF, cell3.PDF, cell4.PDF, and cell5.PDF.

9 The double auctions were conducted using the MUDA software described in Charles R. Plott and Peter Gray (1990). The software for the call market was developed specifically for this project and is available upon request.

10 Consider an Edgeworth hypercube for an economy with ten agents and two goods. Assume that this economy has three equilibria, two of which are stable. Each agent prefers the equilibrium where the terms of trade favor his or her exports, and thus neither is Pareto ranked. Of course, the excess demand function has three roots, and it would be almost impossible to describe it simply. Our treatments are just the reduced form for this economy. The "suppliers" are the agents who export the first good, and the "demanders" are those who import it. Since the first market clears, the second (notional) one must as well. The marginal valuations of the demanders and the "marginal costs" of the suppliers have nothing to do with the sunspot variable. Indeed, the shape of the aggregate excess demand functions is independent of any announcement. Hence the instructions are a convenient reduced form summarizing each person's excess demand (or supply) in a neighborhood of each stable equilibrium.

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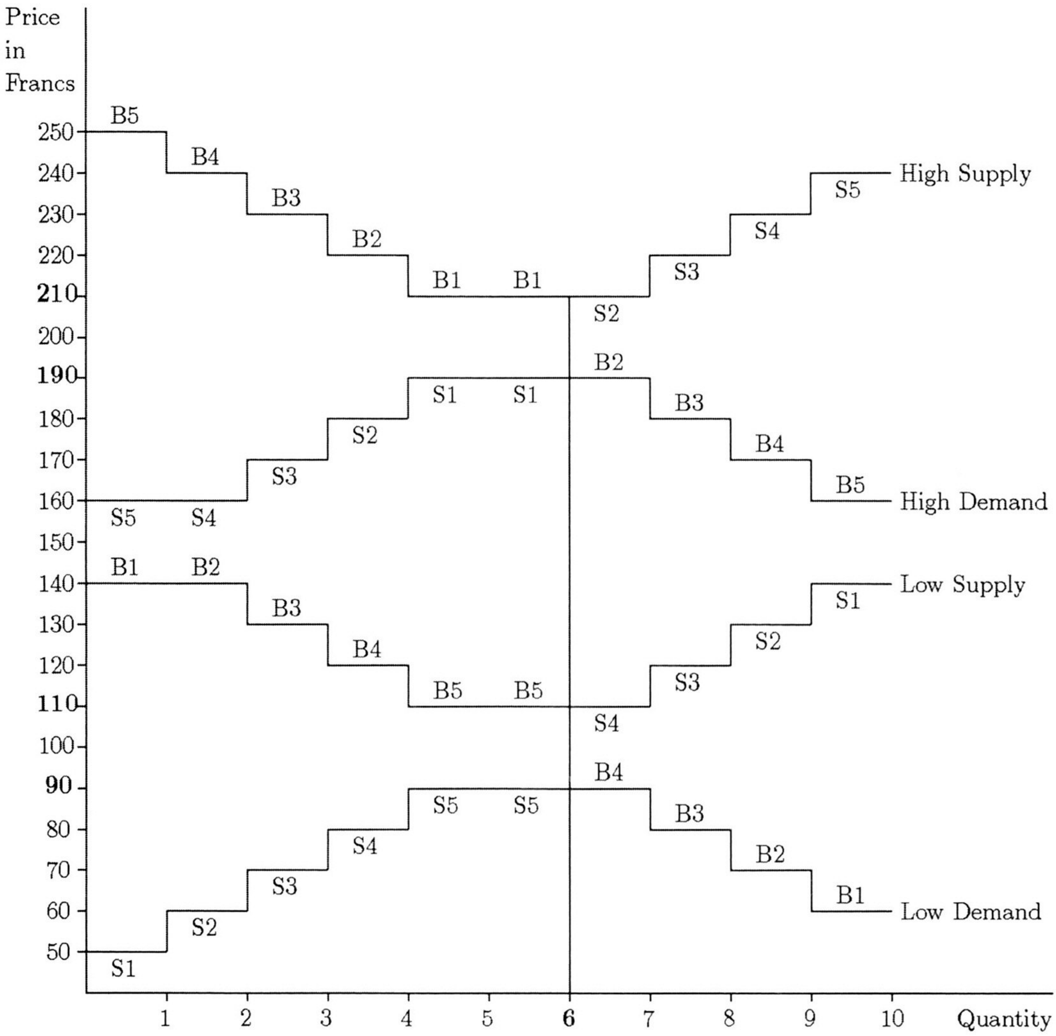

FIGURE 1. INDUCED HIGH AND LOW DEMAND AND SUPPLY, BUYERS: B1–B5, SELLERS: S1–S5

rium prices in the interval [90, 100] and another in the range [190, 210], depending on whether the high or low demand and supply curves were in effect. In all the treatments, we told the subjects that low valuations and costs would occur if the end-of-period median transaction price was less than 150 and high costs and valuations would occur otherwise. Every subject had to make decisions based on uncertainty, not knowing which equilibrium would occur.

The two equilibria are not Pareto comparable by design; some agents' profits are higher in one equilibrium than in the other. If one were Pareto dominant, subjects might coordinate on it as a focal point for their expectations. On the other hand, if each had the same inframarginal rents, then sunspots would matter only in a trivial sense, since every subject's payoff would be independent of the sunspot realization.

In this framework, a *sunspot equilibrium* is just a selection among the certainty equilibria in which the agents' actions are conditioned upon the realization of a publicly observed random variable. The canonical example is to transact at prices in a neighborhood of 100 if one sunspot

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TABLE 2—PREDETERMINED SEQUENCE OF ANNOUNCEMENTS

Period	7	8	9	10	11	12	13	14	15	16
Announcement	Low	High	Low	Low	High	High	Low	High	High	Low

realization occurs and at those near 200 otherwise.

We would like to emphasize that this environment allows for the simplest type of sunspot equilibrium that Cass and Shell (1983) study: randomization over certainty equilibria. It is obviously good science to use the cleanest possible treatment to test the empirical existence of an equilibrium concept whose theoretical implications are profound. Using a time-dependent state variable, as is the norm in some macroeconomic models of sunspots, would complicate the treatments unnecessarily. Finally, the fundamentals for this economy are obviously uncorrelated with the sunspot variable since they are the underlying (constant!) preferences and endowments that give rise to an economy with two stable equilibria.

During the first three periods of every session, we trained subjects by eliminating the low equilibrium; buyers had only high valuations, and sellers had only high costs. During the next three periods, we eliminated the high equilibrium analogously. The primary purpose of the training periods was to allow the subjects to learn how to use the computerized software while replicating two different static environments. A secondary purpose of the training was to make the two equilibria focal points for the subsequent periods in which extrinsic uncertainty was allowed full and free rein. In essence, subjects were being exposed to the language of the sunspot equilibrium at the start of every session.

Of course, in periods 7 through 16, either equilibrium was possible. At the beginning of each period, there was a public announcement based upon a random variable. The usual announcement was: "The forecast is high," or "The forecast is low."

It is important to give the exact text of the relevant instructions. In the treatment where the experimenter made the announcement, the instructions read:

> "Beginning with period 7, the experimenter will make an announcement at the beginning of each period. The announcement will be either that 'the forecast is high' or that 'the forecast is low.' It is important that you understand that these announcements are only *forecasts;* they may be wrong, and they do not determine in any way your actual costs or values in that period. Indeed, the experimenter does not have any more information than you do. Remember that your actual costs and values depend only upon the official median price for that period."

In keeping with the spirit of the literature on sunspots, we used a random number generator to determine the sequence of announcements. Since the sequence of announcements is an obvious control variable, the sequence in Table 2 was used in every session in cells 1 and 3.

In the treatment where a public coin flip was used, the instructions read:

> "Beginning with period 7, an announcement will be made at the beginning of each period. The announcement will be either that 'the forecast is high' or that 'the forecast is low.' This forecast will be determined by flipping a coin. Anyone who wants to can come up and look at the coin and how it landed. If the coin lands heads up, the person who flipped it will announce that the 'forecast is high.' If it lands tails up, that person will announce that the 'forecast is low.' The experimenter will ask each of you to take a turn flipping the coin. When it is your turn, flip the coin in the air and let it land on the floor. Anyone can come up at any time and make sure that the person making the announcement is telling the truth. I will now let everyone see that this is a fair coin, and I will keep the coin in plain view at every moment during the experiment. Come up and look at the coin now.
>
> It is important that you understand that the forecasts based on the coin flips may be wrong and do not determine in any way your actual costs or values in that

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trading period. Remember that your actual costs and values depend only on the official median price for that period."

In this treatment, the random sequence of announcements will almost surely differ across sessions, so that replication of any particular sequence is highly unlikely.

We chose this coin-flip treatment for two reasons. First, a public randomization device might matter. Second, our findings for the treatment where announcements were made by the experimenter might be subject to a Clever-Hans effect.[11] We were concerned that subjects might place undue reliance on the experimenter's announcement because they were afraid that something nasty might be in store if they tried to deviate from it. Perhaps subjects blindly followed the experimenter's announcement because they wanted to please the professor or had trust in him or her. It is of interest to see whether the outcomes differ when the stochastic process determining announcements is transparent and more obviously beyond the control of the experimenter.

The instructions for all treatments made it clear that announcements were not binding in any way. Indeed, subjects were reminded that their actual costs and values depended *only* upon the official end-of-period median price for that period. Each trader was faced with a decision fraught with uncertainty about which equilibrium would actually occur, and some of them learned by hard knocks that the official price could be quite different from the announcement or from what they had hoped would occur.

In the double auction, subjects were allowed to submit bids or offers as long as they had units left to buy or sell. A trading period lasted for four minutes. Subjects observed the current best bid and offer on their screens and could instantly transact at these prices. The best bid and offer were updated in real time according to the standard improvement rules: a buyer had to increase the standing bid and a seller had to undercut the standing offer. Subjects saw each transaction as it occurred, and the bid and offer on the computer screen were cleared when a deal was struck. (Thus no order book was maintained.) Also, the experimenter reported the current median price based on all transactions that had occurred in that period up to that point.

In the call market, subjects typed positive integers for their two bids or offers. The computer program then sorted all bids and all offers, creating demand and supply schedules. If there was an interval of prices that cleared the market, the software chose the greatest integer not higher than the midpoint.[12] Each subject was informed of the market-clearing price as well as the number of units he or she had bought or sold. The call market mechanism was carefully explained to subjects, using several illustrative examples.

We also had a fifth treatment in cell 5 that focused on whether the semantics of the sunspot variable mattered.[13] This treatment was identical to that in cell 4, but we changed *only two words* in the entire instructions. Now the relevant paragraph reads:

> "Beginning with period 7, an announcement will be made at the beginning of each period. The announcement will be either that 'the forecast is *sunshine*' or that 'the forecast is *rain*.' This forecast will be determined by flipping a coin. Anyone who wants to can come up and look at the coin and how it landed. If the coin lands heads up, the person who flipped it will announce that the 'forecast is *sunshine*.' If it lands tails up, that person will announce that the 'forecast is *rain*.'"

(We have added emphasis to help the reader.) The instructions changed "high" to "sunshine" and "low" to "rain." We chose these words for two reasons. First, we wanted the sunspot announcement to make grammatical sense in common English. Second, we wanted to use a

[11] This effect is discussed widely in experimental psychology. It captures the notion that subjects may respond unconsciously to unwitting cues by the experimenter. Indeed, in the nineteenth century, Clever Hans was a famous German horse who could do arithmetic by tapping out answers with his hoof. Rigorous investigation revealed eventually that he was responding to subtle (often unconscious) cues that his (human) audience gave him.

[12] If there was no such interval, then a lottery was conducted among those on the long side of the market to determine who got to trade.

[13] We are very grateful to an editor and the referees who suggested that we design and conduct this extra treatment.

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mapping from the flip of a coin to the two announcements that did not correspond too closely to high or low.[14] We also made an important change during the first six training periods. Instead of saying that the announcement is "sunshine" during the first three periods and the announcement is "rain" during the next three, we just left these announcements blank. The subjects still converged quickly to the competitive equilibria in the training periods, but they had received no lessons in the simple two-word language of the sunspot variable.

In every treatment, after the sunspot announcement, we asked each subject to record his or her forecast of the median price for the coming period before we opened the market. Although we did not pay them for their forecasts, we explained that recording these data would help them focus on what might happen in the market in the coming period. Also, we kept a running tally of all past announcements and official end-of-period median prices on the blackboard. Thus the subjects' expectations were reinforced by the common public history of the market that was in plain view as the session progressed.

In all treatments, the buyers' payoffs were the difference between their unit values and purchase price, and sellers' payoffs were the difference between their sales price and unit cost. Subjects could—and occasionally did—lose money if they bought too dear or sold too cheap. They were paid in cash, and earnings for a two-hour session averaged around $29 per subject, including a $5 show-up fee.

IV. Experimental Results

We conducted 18 sessions using the five treatments described in Table 1.[15] Sixteen of these sessions involved ten inexperienced subjects recruited from the undergraduate populations of The Ohio State University or the University of Pittsburgh.[16] Three of the sessions in cell 1 and four of those in cell 2 were conducted in Columbus, and the rest were held in Pittsburgh. We obtained very similar findings using both subject pools, so we concluded that the subject pool was not important. Therefore, the nine call market sessions in cells 3, 4, and 5 were done at the University of Pittsburgh.

The experiment has produced three important results. First, *sunspot equilibria really exist.* These equilibria can be implemented and replicated in the laboratory; thus we find strong support for Hypothesis 1. Second, *sunspot equilibria appear to be sensitive to the flow of information.* We observed sunspot equilibria in *every session* with a call market where the meaning of the sunspot variable was clear; in the double auction, they occurred slightly less than half the time. Since a call market has a much more restricted flow of information than a double auction, we conclude that there is support for Hypothesis 2. Third, consistent with Hypothesis 3, *the semantics of the language of sunspots matters.* Our sunspot variable—the announcement of the likely equilibrium—provides the context that enables all agents to condition their expectations appropriately.

To be precise, we shall claim that a sunspot equilibrium occurs only if every time the announcement is high, the median transaction price is 150 or greater, and if every time it is low, the median transaction price is less than 150.[17] We would like to emphasize just how stringent this definition is. We report a success only if ten subjects coordinate on the sunspot variable in every single period. Thus the subjects have to believe in the sunspot variable from the very beginning, and their beliefs must be confirmed in every period. We do, however, allow for some noise in the data. The design predicts that equilibrium quantities are always six, but we occasionally observed market vol-

[14] We did not say "the forecast is heads" and "the forecast is tails" precisely because writing an "H" on the blackboard is just too close to a natural symbol for 'high.'

[15] To keep this section short, we will describe data from five representative sessions. The interested reader can find *all the data* from all 18 sessions in a compressed file at http://economics.sbs.ohio-state.edu/efisher/duffyfisher/data.zip

[16] A referee suggested that we examine the effect of experience on these markets, and we ran two sessions in which the subjects had participated in the same treatment before.

[17] We recognize that there is another "contrarian" sunspot equilibrium, where an announcement of "high" leads to coordination on the low equilibrium and an announcement of "low" leads to coordination on the high equilibrium. We focus on the more natural sunspot equilibrium because it was the only type we ever observed.

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umes that were slightly different. So we will still say that a sunspot occurred even if quantity differs slightly from this benchmark.

A. *Double Auction, Predetermined Experimenter Announcements*

We ran four sessions for the treatment in cell 1 of Table 1. Among these four sessions there was one success (a sunspot equilibrium) and three failures. Failures of the theory typically occur in one of two ways: either the subjects do not coordinate on the sunspot in just a few periods; or they coordinate on a certainty equilibrium in every period. These two possibilities are illustrated in Figures 2 and 3, which show data from the sessions 1 and 2 of cell 1.

The top panel of these and all subsequent figures shows transaction prices and the sunspot predictions. By sunspot prediction, we mean that a forecast of high is associated with the competitive equilibrium where prices lie in the interval [190, 210], and a forecast of low is associated analogously with prices in [90, 110]. For simplicity, the sunspot prediction is represented in our figures as either 200 or 100. One can see in Figure 2 that the sunspot predictions failed in periods 7, 12, 14, 15, and 16 of this session. Figure 3 presents an even starker example, where following the training period, subjects ignored the sunspot announcements and coordinated on the low equilibrium in every period.

The bottom panel of these figures describes aspects of subjects' beginning-of-period forecasts of the median transaction price that would obtain at the end of the period. For each period, the line segment shows the range of subjects' beginning-of-period forecasts. The square represents the median of the ten subjects' beginning-of-period forecasts, and the cross is the actual median transaction price at the end of the period; this end-of-period median transaction price determined whether high or low values and costs would be used in calculating earnings. One can see that the markets converged to the unique equilibrium during the first six training periods and that agents' expectations about the actual median transaction price were being formed appropriately. In the bottom panel of Figure 2, we see that, with few exceptions, subjects' forecasts never converged enough to conform to the sunspot announcements during periods 7 through 16 when both equilibria were possible. In the bottom panel of Figure 3, we see that in period 8 the median subject beginning-of-period forecast turned out to be quite wrong; this was the first period in which the sunspot announcement was high. After that, subjects chose to ignore the sunspot, and their forecasts became largely consistent with the low equilibrium that occurred in periods 7 through 16. Still, at least one subject in every period appears to have maintained a belief that the sunspot variable had predictive power, as evidenced by the range of subjects' beginning-of-period forecasts.

In analyzing the first bids and offers from all the sessions in this treatment, we came to believe that demanders who benefited the most in the high equilibrium often tried to induce it by making a high opening bid; likewise suppliers who benefited the most in the low equilibrium often made a low first offer. With these opening bids or offers, the standard improvement rule for a double auction (which is public information) constrains subsequent bids to be higher or subsequent offers to be lower. Thus the flow of information in a double auction does seem to allow inframarginal bids and offers to serve as signals independent of the sunspot realization. Initial transactions are very important, a fact that has been found in field data as well. In the working paper version of this manuscript (Duffy and Fisher, 2003), we provide a model showing how early transactions can lead to a cascade that mitigates the need for a sunspot variable as a coordinating device.

B. *Call Market, Predetermined Experimenter Announcements*

There were three sessions in cell 3, and a sunspot equilibrium occurred in every one. Figure 4 shows the data from the first session of this treatment. All of the data from the sessions in cells 3 and 4 look like those in Figure 4, in the sense that there is perfect coordination on the sunspot announcement in every period of every session. Figure 4 plots the single market-clearing price, the volume of units traded in each period, and the theoretical sunspot predictions. This figure contrasts sharply with Figures 2 and 3; the evidence for sunspot equilibria is quite clear. A close analysis of the data suggests

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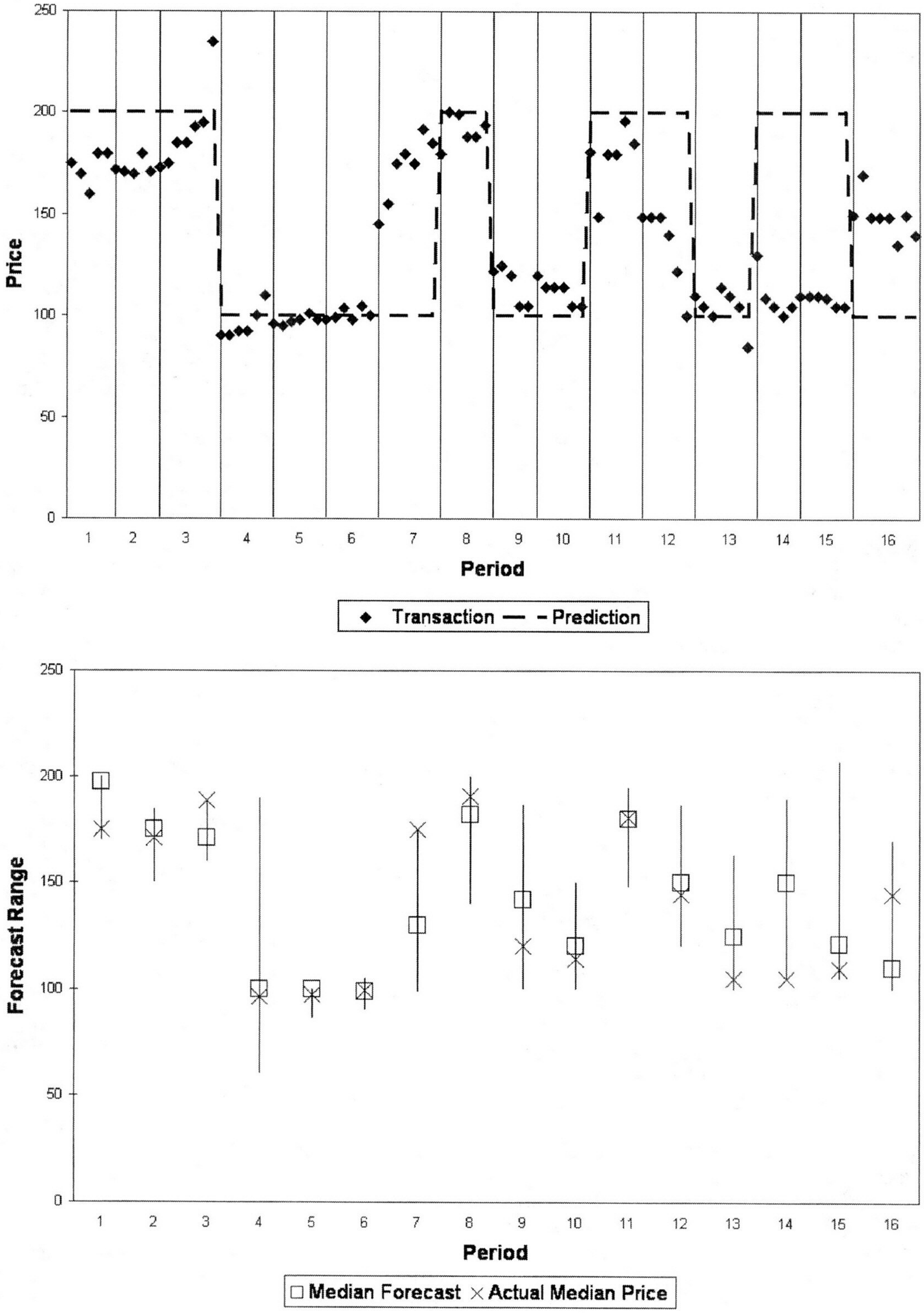

FIGURE 2. CELL 1, SESSION 1

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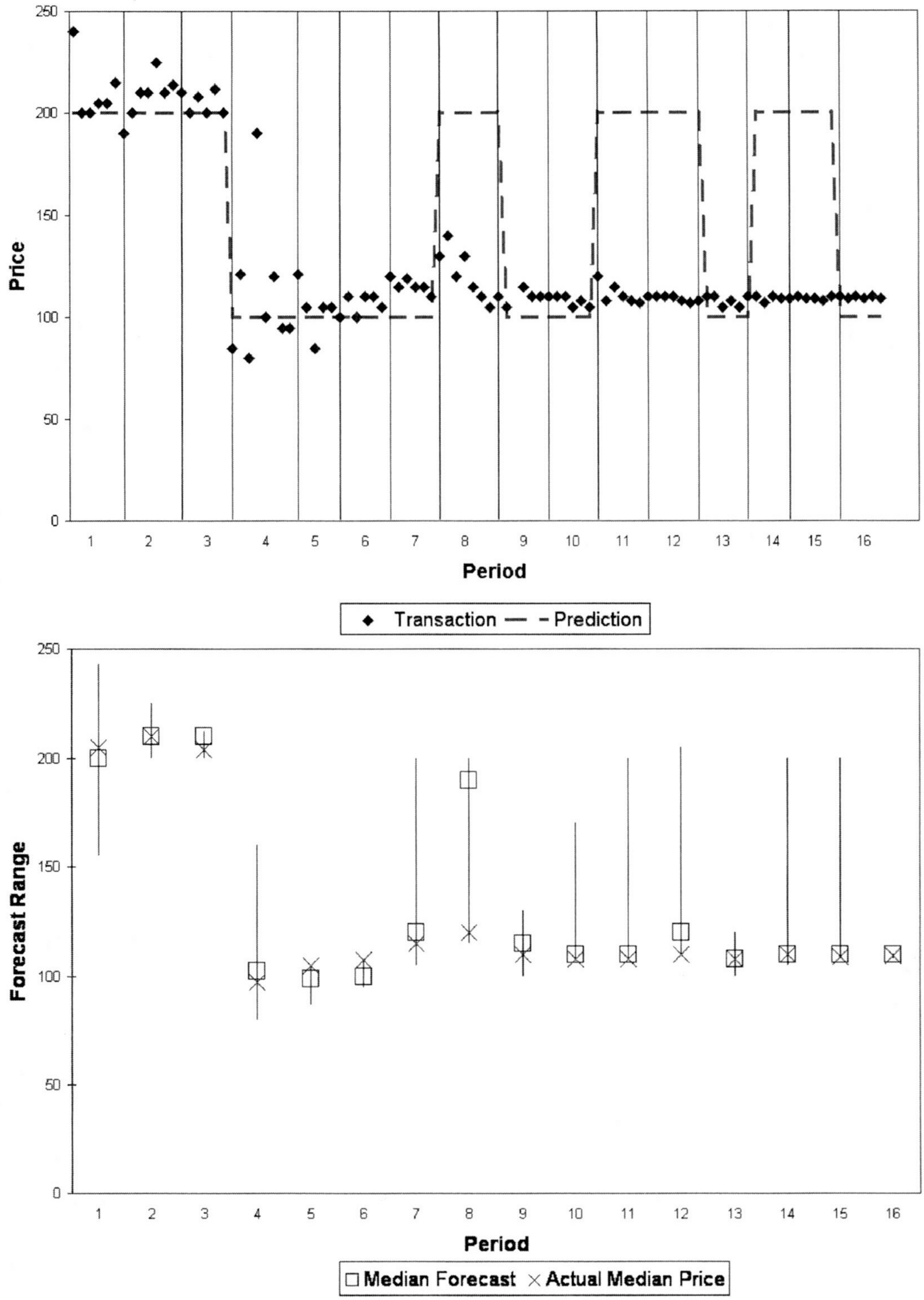

FIGURE 3. CELL 1, SESSION 2

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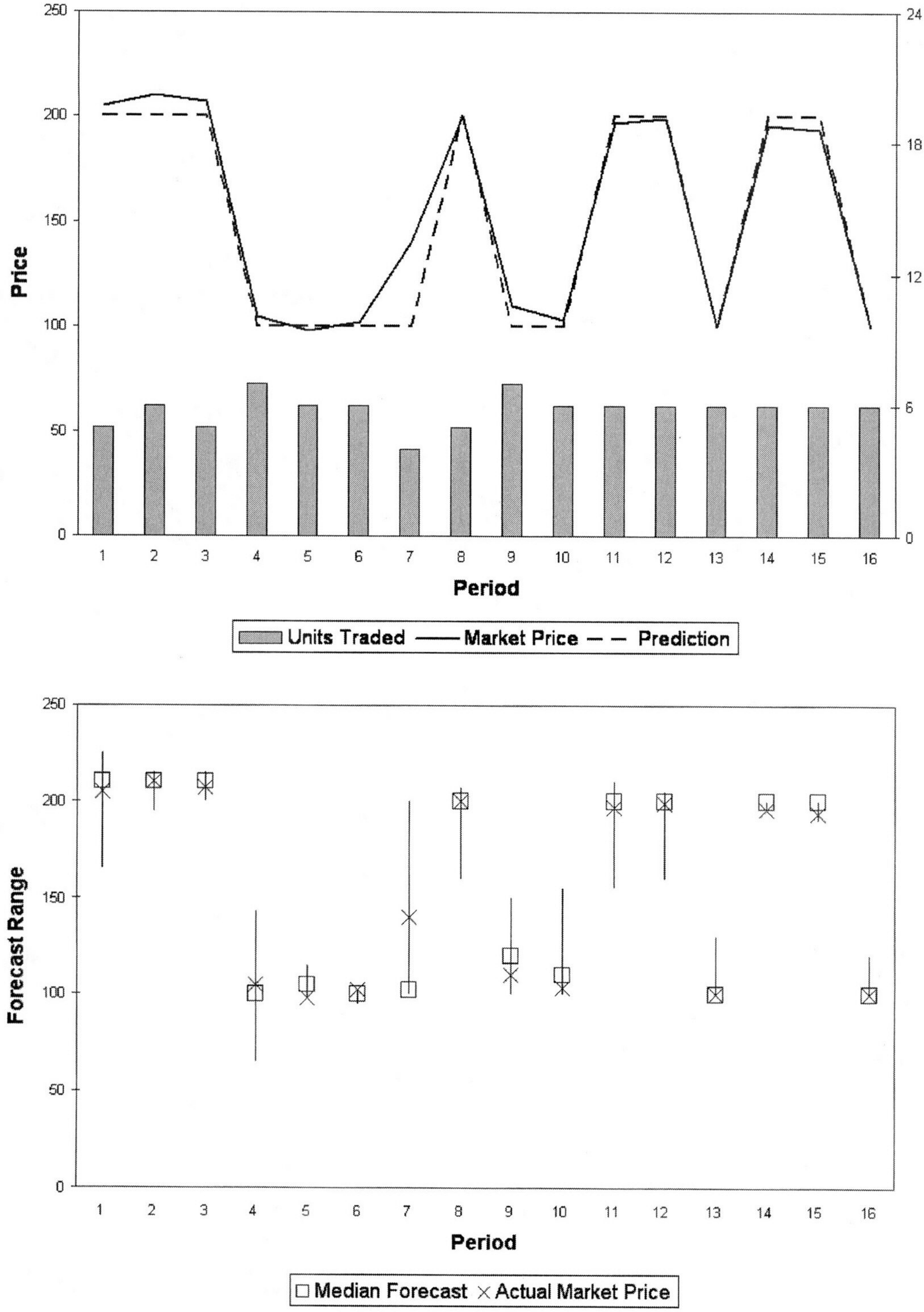

FIGURE 4. CELL 3, SESSION 1

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that a few subjects submitted bids and offers in early periods in a strategic attempt to influence the current price, but this is a much more formidable task in a call market than in a double auction. Indeed, it takes about five or six independent bids or offers—each betting in essence against the sunspot announcement—to move the price across the threshold that defines the equilibrium. A subject knows only her own actions and the price that is revealed at the end of the period. This paucity of information makes it extremely difficult to influence the equilibrium strategically, and the risk of making the wrong bid or offer is just too great to try to buck the sunspot announcement. Also, it is obvious that the agents learn to believe in these announcements because the distribution of forecasts becomes very accurate after the eighth period.

In Duffy and Fisher (2003), we consider a simple game and show that the strategy where subjects follow the announcement and truthfully reveal their values and costs is a correlated equilibrium. We argue that the data from the call market sessions are consistent with the notion that subjects have played this correlated equilibrium.

C. *Double Auction, Announcements by Public Coin Flips*

There were five sessions in cell 2, and we had three sunspot successes and two failures. Figure 5 shows the data from the first session. This treatment is a double auction where each of the subjects takes a turn flipping a coin and making the sunspot announcement. It is quite interesting that in this treatment we observe sunspot equilibrium in three of five sessions. In the session shown in Figure 5, it is obvious that there was a great deal of uncertainty about the efficacy of the sunspot announcement as a coordinating device during the ninth period. After that, the subjects came to believe in the sunspot. A similar result obtains in the other two sessions where sunspot equilibria occurred. In the two sessions of cell 2 where sunspot equilibria did not happen, the subjects quickly coordinated on either the low equilibrium or the high one, so illustrations of those data would be analogous to Figure 3. We conclude that sunspot equilibria in double auctions are possible, but this outcome may be delicate.

D. *Call Market, Announcements by Public Coin Flips*

There were three sessions in this cell, and we observed a sunspot equilibrium in every one. In this treatment, the subjects took turns flipping a coin and making an announcement based on the outcome. The data for these three sessions look exactly like those in Figure 4, except that the announcement sequence is random. We conclude that sunspot equilibria in the call market are robust to the manner in which random announcements are made. Also, the volume of transactions and the agents trading are efficient, given that the sunspot announcements act as a coordination device.

E. *Call Market, Announcements of "Sunshine" and "Rain" by Public Coin Flips*

The sessions in this cell changed two words from the treatment in cell 4. The words "The forecast is high" became "The forecast is sunshine," and "The forecast is low" became "The forecast is rain." Also, the subjects were not trained on any announcement in the initial six periods. There were three sessions in this cell, and *not a single one had a sunspot.* Figure 6 shows data from the first session in cell 2. It is clear that the equilibrium and the forecasts in the training periods were not affected by the lack of an announcement. But once the subjects had to rely on the sunspot announcements during the last ten periods, they were at a complete loss as to how to interpret them.[18] Indeed, exchange became fully efficient only in the last three periods in this session, when all six units were traded and the agents had come to believe with high precision that the low equilibrium was going to occur in every period. The bottom panel of Figure 5 shows a beautiful example of monotone convergence of expectations, as the

[18] Indeed, the third session in this cell was conducted on 1 April 2004, and one of the subjects asked if the "sunshine" and "rain" announcements were an April Fools' Day joke!

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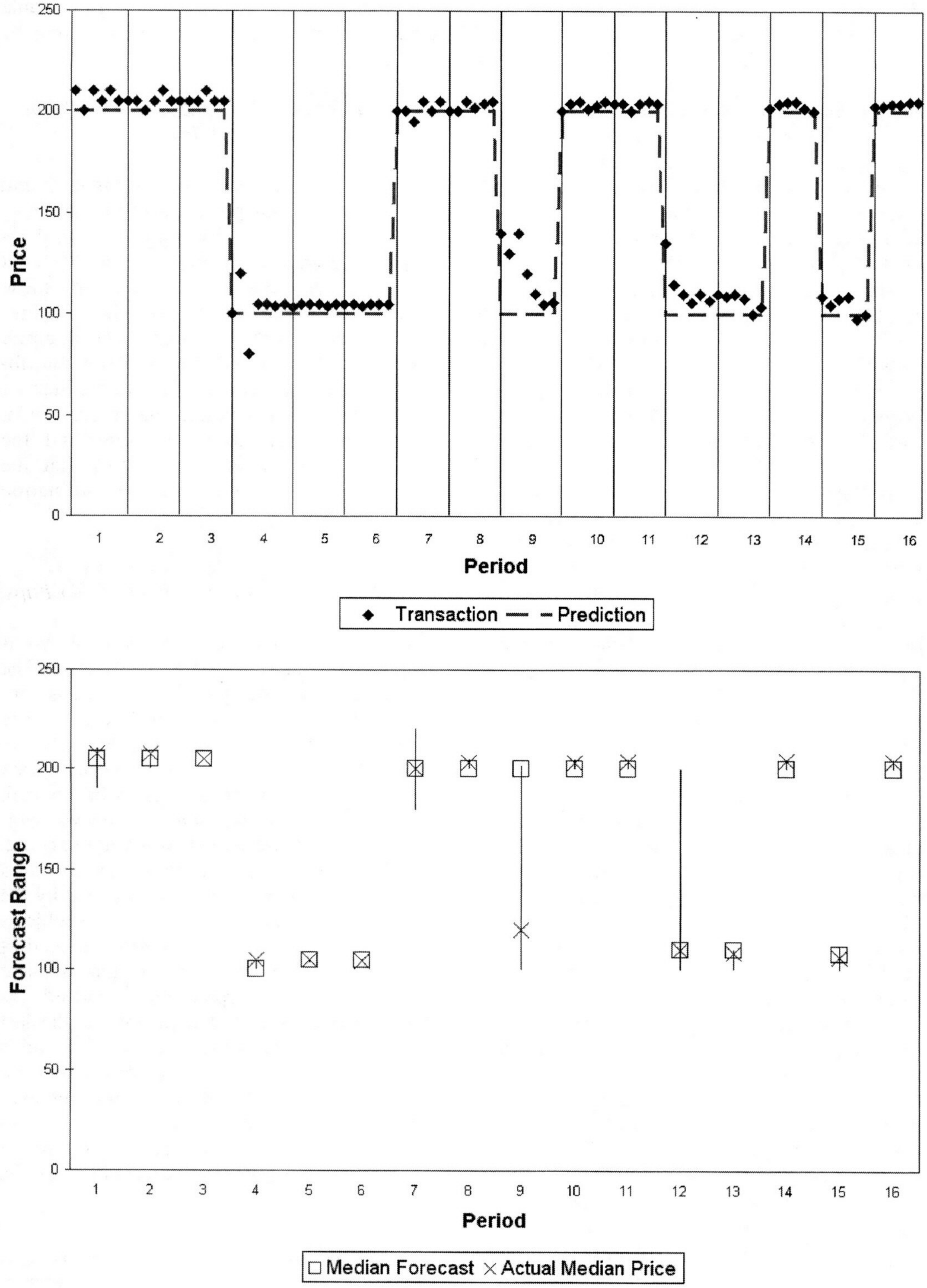

FIGURE 5. CELL 2, SESSION 1

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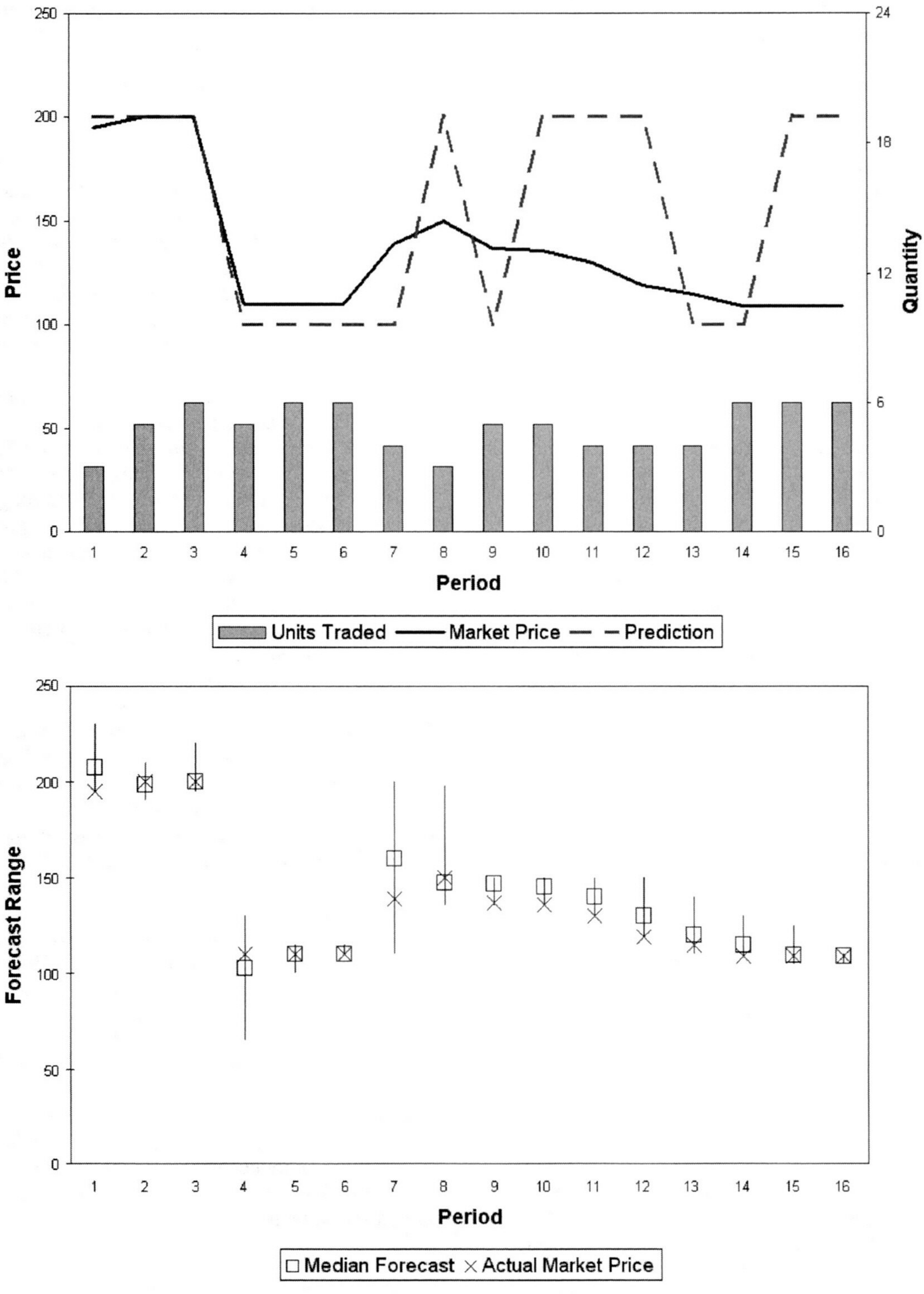

FIGURE 6. CELL 5, SESSION 1

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agents learned to believe that only the low equilibrium would matter.

The data from the other two sessions in this cell were very similar. The subjects in the second session ignored the sunspot announcements and coordinated on the high equilibrium; their forecasts also ignored the announcements and showed a nice monotone convergence to the high equilibrium. The third session had a mix of experienced subjects from the earlier two sessions, with a majority having experienced coordination on the high equilibrium. Again, the subjects ignored the sunspot announcement and coordinated on the high equilibrium.

F. *The Effect of Subject Experience*

What was the effect of subject experience in these markets? The fifth session of cell 2 (the double auction with coin flips) and the third session of cell 5 (the call market with sunshine and rain forecasts) had subjects who had been in almost identical prior treatments. It seemed as though the experience of the majority was brought to bear in the new sessions. In particular, there was a second sunspot equilibrium in the fifth session of cell 2, perhaps because the majority of subjects in this session (seven of ten) had experienced a sunspot equilibrium the week before. Thus the actions of the "gang of seven" may have been able "to persuade" the minority of three—who had experienced a session with coordination on the high-certainty equilibrium—to follow the sunspot announcement.

The third session of the call market with sunshine and rain announcements had the agents coordinating on the high equilibrium. In this case, a majority of six subjects, who had seen the very same outcome in a prior session, were able to "persuade" the minority of four, who had seen coordination on the low-price certainty equilibrium, to follow along with them to the high-price equilibrium. They did this even though there was no means of communication at all! If most people are submitting high bids and offers, you buck this trend at your peril. Indeed, many subjects "sat out" periods 7 through 9 by offering very low bids or high offers, and the market became fully efficient only in the last few periods, when it became evident that everyone was coordinating on the high equilibrium.

G. *Discussion of the Results*

The data provide clear support for our three hypotheses. First, sunspot equilibria do exist in a controlled environment, and we are the first to have produced them. Indeed, sunspots occurred in ten of the 15 sessions in the main treatments in cells 1 through 4. Second, the market mechanism is also important. In the call market, we found that sunspot equilibria always occurred. This finding is readily replicated, no matter how the announcement is made. By contrast, sunspots do not occur every time in the double auction. Third, the semantics of the sunspot language clearly makes a difference. In cell 5, we disrupted the use of the sunspot variable simply by changing two words and not training subjects in the meaning of the new sunspot announcements. Also, in the main treatments, the "contrarian" sunspot equilibrium, where the subjects coordinate on the equilibrium that is the exact opposite of the common language announcement, was never observed.

The outcomes from the 18 sessions are summarized in Table 3. Let us focus on the data from cells 1 through 4, the treatments where the semantics of the sunspot variable are clear. We see that there were four sunspot successes and five failures in the double auction treatments. There were six successes and *no* failures in the call market treatments. Imposing the null hypothesis of a random assignment of successes across the type of market, Fisher's exact test[19] has a p-value of 0.044. Thus the hypothesis can be rejected for a test of size 5 percent. What accounts for this difference across kinds of markets? It is likely that success breeds success in learning the language of sunspots. The call market is so effective in creating and reinforcing the belief in a semantically salient sunspot variable because the common language interpretation of the sunspot variable realization, and the public nature of the announcement, effectively resolve any doubt about how others will solve the coordination problem.

[19] See Sidney Siegel and N. John Castellan, Jr. (1988) for the precise details of this nonparametric test.

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TABLE 3—EXPERIMENTAL OUTCOMES

		Announcements	
		Predetermined by experimenter	Public coin flips
Market mechanism	Double auction	Cell 1 1 Success 3 Failures	Cell 2 3 Successes 2 Failures
	Call market	Cell 3 3 Successes 0 Failures	Cell 4 3 Successes 0 Failures
Sunspot semantics	Call market with "sunshine" and "rain" announcements	Cell 5 0 Successes 3 Failures	

On the other hand, the use of a public coin flip or private randomization device (predetermined by the experimenter) does not seem to matter. As cells 1 through 4 in Table 3 reveal, there were four successes and three failures of sunspot theory when the sequence of announcements was predetermined, and six successes and two failures when a public coin flip was used. Imposing the null hypothesis of no difference across the type of randomization device, Fisher's exact test has a p-value of 0.61.

V. Conclusions

Experimental economics has been perhaps most successful in illustrating how markets work. Experimentalists have repeatedly found that institutions matter: different kinds of markets give rise to different outcomes. Until now, models whose equilibria relied on the existence of "animal spirits" have been useful and elegant theoretical curiosities. But we have given these models real empirical bite. We are the first to provide *direct* evidence that extrinsic uncertainty can be an important source of volatility in real markets. Furthermore, we have shown that the efficacy of sunspot variables in coordinating expectations depends on the flow of information, and this finding has important theoretical implications. Our sunspot announcements serve as a reliable coordinating device only when information flows slowly, as in a closed-book call market; in the double auction, sunspots occur often enough, but much depends on the faster and sometimes confounding flow of information in this environment. The theory of sunspot equilibrium has been developed typically in a Walrasian framework, where the flow of information is no slower or faster than the speed at which a market clears. Our findings indicate that it is important to model information flows while the market is clearing.

Much of the interest in correlated equilibria and sunspots stems from the possibility that public signals allow one to achieve more than just the convex hull of the certainty equilibria. Thus we have tested for the least interesting and perhaps least important sunspot possibilities. This is a weakness of our experiments, and we think that analyzing treatments with more nuanced sunspots is an important area for future work. These treatments represent only the first step in what we hope will grow into a broader branch of experimental research in macroeconomics and finance.

Our experiments also suggest that it is important to consider the semantics of the language of sunspots. When we had subjects flip a coin, we asked them to say that "the forecast is high" if heads came up and "the forecast is low" if tails came up. This is quite different from flipping a coin, observing that it lands heads, announcing "the forecast is sunshine," and then expecting subjects to coordinate on some equilibrium by themselves, as though every person can simultaneously and independently come up with a semantic interpretation of what the event heads *qua* "sunshine" might mean. Thus it may not be enough to train subjects with a blinking square cycling between two colors on the computer screen, but it certainly is adequate to state publicly that "the forecast is high" or "the forecast is low." Likewise, there may be a sunspot in the performance of the U.S. stock market based

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upon whether the National Football Conference or the American Football Conference wins the Super Bowl, but there will be no empirically testable hypothesis until it has become common knowledge that the language of that sunspot depends upon everyone knowing which teams belong to each conference.

The fact that sunspot announcements serve as coordinating devices has important implications for financial markets in the field. Indeed, one might argue that an important aspect of monetary policy in the United States in the last few years has been trying to anticipate and perhaps mitigate the effects of sunspot equilibria in major financial markets. Thus, showing that sunspot equilibria may well depend upon the flow of information has very real implications for the architecture of these markets. For example, our findings would seem to indicate that stock trade suspension rules that are commonly used in the field may actually increase the possibility of sunspot equilibria.

In these experiments, the sunspot realizations help, paradoxically, to ensure that the market is conditionally fully efficient. Indeed, when agents try unsuccessfully to manipulate information strategically, they pay a price because the wrong inframarginal bids or offers are submitted. This implies that the resultant equilibrium does not maximize ex post social surplus. In field markets, the connection between welfare and sunspots is not so apparent, but it may be a very real part of any financial system.

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