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Speculative runs on interest rate pegs

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ABSTRACT

We analyze a new class of equilibria that emerges when a central bank conducts monetary policy by setting an interest rate (as an arbitrary function of its available information) and letting the private sector set the quantity traded. These equilibria involve a run on the central bank's interest target, whereby money grows fast, private agents borrow as much as possible against the central bank, and the shadow interest rate is different from the policy target. We argue that these equilibria represent a particular danger when banks hold large excess reserves, such as is the case following periods of quantitative easing. Our analysis suggests that successfully managing the exit strategy requires additional tools beyond setting interest-rate targets and paying interest on reserves; in particular, freezing excess reserves or fiscal-policy intervention may be needed to fend off adverse expectations.

1. Introduction

Until the last few years, most central banks (CBs) around the world conducted monetary policy by setting targets for short-term interest rates. Maneuvering interest rates as a way to achieve low and stable inflation is now regarded as a success story, and it is widely expected that it will return to be the dominant tool of monetary policy as soon as the economy and inflation recover enough to warrant moving away from the zero lower bound on nominal interest rates.

The aftermath of quantitative easing implies subtle differences for interest-rate management that have however potentially dramatic implications for the control of the price level. Taking the Federal Reserve System as an example, before 2008, day-to-day implementation of a given interest-rate target was entrusted to open-market operations undertaken by the trading desk of the Federal Reserve Bank of New York; the trading desk retained full control of the *quantity* of monetary base available for transactions.[1] In the aftermath of quantitative easing, the monetary base is much larger than what is demanded purely for transaction reasons, and, during the period of exit, control of interest rates is expected to be achieved by setting a *price*, the interest paid on bank reserves. Interest on reserves acts as a floor on the interest rate in the interbank

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[1] For further discussion of the tools used by the Federal Reserve for managing interest rates, see Goodfriend (1991).

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market, as described in Goodfriend (2002). By setting an appropriate interest on reserves, it is expected that banks will not attempt to lend out their excess funds on deposit at the CB, and that interbank rates will remain close to this floor. In this case, the excess monetary base that is not needed to carry out everyday transactions would remain effectively parked at the CB. But what would happen instead if banks and the public lost confidence in the central bank's ability to keep inflation in control and started trying to use those reserves at once? In this paper, we consider this possibility and we argue that purely setting interest on reserves is an insufficient tool to achieve price stability; we show that this policy is subject to "runs." A CB that persisted using only interest on reserves as its policy tool in the face of a run would face hyperinflation. Other, more likely exit scenarios in such adverse circumstances involve freezing excess reserves or fiscal-policy intervention; these scenarios thus deserve further attention.

We conduct our analysis in a simple environment that features flexible prices and a standard cash-in-advance constraint, where the intuition for our results is simple and transparent; however, our results would extend to models with frictions. In this setup, we introduce a CB that sets the one-period interest rate; this interest rate need not be fixed, but rather may depend in arbitrary ways on all the information that the CB has at the moment it makes its decision. The private sector is free to choose quantities traded with the CB, *up to a limit.* In the case of interest on reserves, this limit is zero: banks cannot hold negative reserves. More generally, the CB could (and does) allow borrowing, but this is limited, typically by collateral requirements. We show that setting a policy rate in this way leads to multiple equilibria. Some of the equilibria are familiar and common to the environments where limits to money growth are not considered.[2] However, new equilibria emerge, where money growth and inflation are higher. These equilibria involve a run on the CB's interest target: the private sector borrows as much as possible from the central bank, money in circulation grows fast, and the shadow interest rate in the private market is different from the policy rate.

In our environment, the severity of a run is affected by the size of the trades that the private sector can undertake against the CB. In the case of quantitative easing and interest on reserves, this is determined by the size of the CB's balance sheet. More generally, if government bonds are an important source of collateral to borrow from the CB, fiscal policy plays a prominent role in defining the characteristics of equilibria that feature runs.[3] This is a new channel by which excessive deficits affect price stability, and it is independent of the familiar unpleasant monetarist arithmetic of Sargent and Wallace (1981) and of the fiscal theory of the price level (Leeper, 1991; Sims, 1994; Woodford, 1994). In fact, we deliberately rule out these alternative channels of monetary-fiscal interaction by postulating fiscal rules that ensure long-term budget balance independently of the path of inflation.

In an extension of our model, we consider what happens if the central bank sets interest rates in a (possibly narrow) sliver of the market, rather than standing ready to buy and sell a large swathe of securities at a set price. When no run occurs, we show that the equilibrium remains the same independently of the size of the market in which the central bank operates. But if a run occurs, the consequences are more limited the more circumscribed this market. This provides a rationale for why central banks may find it attractive to set targets only for very short-term interest rates (a relatively small portion of the entire bond market), but refrain from doing the same for a broad spectrum of the yield curve.

This extension also allows us to consider the difference between targeting interest rates on Treasury paper and obligations of the CB itself (excess reserves). In the absence of a run, Eggertsson and Woodford (2003) and Goodfriend (2014) explain why quantitative easing is neutral if it is conducted by purchasing short-term Treasury securities that pay the same interest rate as the newly created excess reserves (and serve the same liquidity needs at the margin). In the event of a run, however, short-term Treasury securities and excess reserves need not be equivalent, and the size of the CB balance sheet is important. It is easy for the CB to stop buying Treasury securities in the face of large unexpected supply by the banking sector, thereby retaining control over the monetary base in circulation. Conversely, preventing banks from attempting to use their excess reserves involves changes in reserve requirements, a tool that central banks in developed economies have not used recently and that might be difficult to deploy, for political and legal reasons, on the scale needed to reabsorb the current levels of excess reserves in Japan, the United States, or the United Kingdom.[4] That is, the CB converting *excess* reserves to *required* reserves precisely because commercial banks wish to withdraw them could be interpreted as the CB defaulting on its promises.

In the simple setup that we describe, in the event of a run, households force the central bank to its bound in a single period. In practice, the unfolding of a run would be slowed by a number of frictions that may prevent all households from running at once with all of their nominal wealth; these frictions may take the form of limited participation in bond markets (see, for instance, Grossman and Weiss, 1983; Alvarez and Atkeson, 1997; Alvarez et al., 2009), noisy information about other households' behavior, or the presence of long-term bonds whose price is not pegged by the central bank.

Our model sheds light on two historical episodes. In the more extreme case, the policy of the Reichsbank during the German hyperinflation fits well within our model. As mentioned by Sargent (1983), the German Reichsbank discounted

[2] Examples of these equilibria are those identified by Benhabib et al. (2001a,b) and those discussed in Cochrane (2011). In those equilibria, the Fisher equation linking interest rates and expected inflation remains valid, while the speculative runs that we identify involve high inflation and severe monetary distortions coexisting with low (official) nominal interest rates.

[3] Arguably, the size of a CB's balance sheet is a measure of "in-house" fiscal policy run by the monetary authorities, since it involves managing the magnitude of the CB's interest-bearing liabilities.

[4] As an example, in the United States, there are limits imposed by law on the Federal Reserve's ability to alter reserve requirements (Feinman, 1993); an Act of Congress would thus be needed to freeze reserves on the scale that would be required to absorb the current level of excess reserves.

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Treasury and commercial bills at fixed nominal interest rates in 1923; these rates were far too low to equilibrate loan markets given expected inflation, and a run of precisely the type that we describe occurred: the policy added fuel to the hyperinflation by causing the Reichsbank to greatly increase the money supply and transferring this money to the government and to those private entities lucky enough to borrow from the Reichsbank at the official discount rate.

In a more relevant example for the current situation, the Federal Reserve System successfully managed an "exit strategy" from quantitative easing once before. During the Great Depression, commercial banks accumulated sizeable excess reserves deposited with the Federal Reserve, that lasted through the early 1950s. In the 1940s, up to the Treasury accord of 1951, the Fed managed monetary policy by pegging interest rates. However, at various points this led to inflationary tensions. As discussed by Eichengreen and Garber (1991), the Fed did not rely purely on interest rates to subdue them, but it rather adjusted *required* reserves to regain direct control over the quantity of funds that would be available to start a full-blown speculative attack. In this light, our analysis suggests a new role for the "twin-pillar" doctrine of paying attention to monetary aggregates (both broad and narrow) as well as interest rates in designing appropriate monetary policy rules.[5]

2. The basic cash-in-advance model

Consider a version of the cash-in-advance model. There are a continuum of households of unit mass and a government/monetary authority. Time is discrete with dates $t \in \{0, 1, 2, \ldots\}$. In each period, the timing is as follows: first, the realization of a sunspot variable s_t is observed by all. Without loss of generality, s_t is i.i.d. with a uniform distribution on $[0, 1]$. All variables with a time-t subscript are allowed to be conditional on the history of sunspot realizations $\{s_j\}_{j=1}^{t}$. After s_t is observed, the government sets nominal taxes, T_t, possibly as a function of everything that has happened up to that point in time. Then, asset markets open. In these asset markets, households purchase new bonds from the government using money. Monetary policy is assumed to take the form of a pure interest rate rule. That is, the government sets a nominal interest rate, R_t, at which is stands ready to trade money for new one-period risk-free government bonds, where this rate can also depend on the entire past history up to date $t-1$.[6] In the asset market, households may also trade zero-net supply securities with other households; these securities can be contingent on the future realization of the sunspot.[7]

The description above assumes that the CB sets its interest rate as the discount factor on government bonds, as was the case for the German Reichsbank. The same equations apply in the case of modern central banks in the aftermath of quantitative easing, simply by relabeling variables appropriately. Specifically, in this case $-T_t$ represent seigniorage payments from the central bank to treasury (that are in turn rebated to households), and R_t is the interest on excess reserves; in this case, "money" represents cash or required reserves that banks must hold if they expand their deposits, and "bonds" are excess reserves that do not provide liquidity services and are held only if they offer the same return as competing private assets.[8] In what follows, we will continue to use the "Reichsbank labels," except when deriving remarks that specifically apply to interest on reserves.

After the asset markets, a goods market opens. In the goods market, households produce the consumption good using their own labor for the use of other households (but, as usual, not their own household) and the government. Each household has one unit of time and a constant-returns-to-scale technology that converts units of time into units of the consumption good one for one. Households use money to purchase units of the consumption good produced by other households. The government uses either money or bonds (it is immaterial which) to purchase $G_t = \overline{G} \geq 0$ units of the consumption good.

Fig. 1 summarizes the events within each period.[9]

Let M_t denote the amount of money in circulation at the end of the asset market in period t, after taxes are paid. Let B_{t-1} be the nominal amount of government bonds payable at date t. (If $B_{t-1} < 0$ then it represents a debt that households owe the government at date t) The households start with initial nominal claims W_{-1} against the government.[10]

Consider a sequence $\{P_t, R_t\}_{t=0}^{\infty}$, where P_t is the nominal price of a unit of the consumption good at date t and R_t is the nominal risk-free rate between period t and $t+1$ at which the government trades with private agents. A government policy $\{T_t, M_t, B_t\}_{t=0}^{\infty}$ is said to be feasible given $\{P_t, R_t\}_{t=0}^{\infty}$ if for all $t > 0$

$$B_t = (1+R_t)\left[P_{t-1}\overline{G} - T_t - M_t + M_{t-1} + B_{t-1}\right], \tag{1}$$

[5] For a discussion of the twin-pillar doctrine, see Lucas (2007).

[6] Not allowing this rate to depend on date t information rules out the government setting a schedule of interest rates as a function of the quantity of money households choose to retain.

[7] In a representative-agent context, the presence of private securities in zero net supply does not alter the equilibrium allocation, but it will be convenient to have an explicit private-market interest rate to contrast with the rate set by the central bank.

[8] When we follow this interpretation, we still separately assume that treasury taxes and debt are set so that the fiscal theory of the price level does not apply.

[9] Our results are robust to a variety of different timing assumptions. However, it is important that households know the interest rate at which they trade with the central bank: we do not allow the central bank to unilaterally set its terms of trade ex post, after households have committed to their bond purchase decisions.

[10] These claims represent money and maturing bonds, before paying period 0 taxes.

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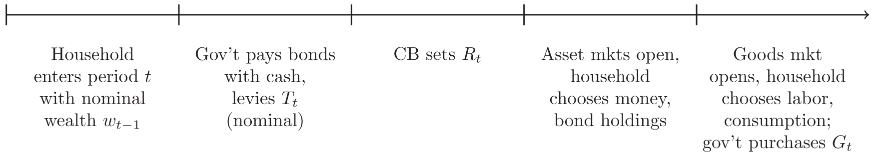

Fig. 1. Timeline of events within period t.

with the initial condition

$$B_0 = (1+R_0)[W_{-1} - M_0 - T_0]. \tag{2}$$

In what follows, we use lower-case letters to indicate individual household choices and upper-case variables to indicate aggregates: as an example, m_t are individual money holdings, and M_t are aggregate money holdings. In equilibrium, lower and upper-case variables will coincide, since we consider a representative household.

Households are subject to a cash-in-advance constraint: their consumption must be purchased with money.[11] A household's path is given by $\{c_t, y_t, a_{t+1}, b_t, m_t\}_{t=0}^{\infty}$, where a_{t+1} are holdings of privately-issued contingent securities maturing in period $t+1$.[12] In addition, households are potentially constrained in their holdings of government securities to a set $\mathcal{B}_t$. We will first explore the case in which $\mathcal{B}_t$ is the entire real line, and we will then explore the implications of setting a limit to private indebtedness against the government.

Let Q_{t+1} represent the asset pricing kernel. That is, $Q_{t+1}(s_{t+1})$ is the probability weighted price, in terms of date t consumption, of s_{t+1} contingent consumption. Thus the price of date $t+1$ non-contingent consumption in terms of date t consumption is $E_t[Q_{t+1}] := \int_0^1 Q_{t+1}(s_{t+1})\, ds_{t+1} = 1/(1+\hat{R}_t)$, where $\hat{R}_t$ is the risk-free rate at which households trade with each other.

A household's date t expenditures on date $t+1$ contingent assets is

$$E_t[a_{t+1}Q_{t+1}] := \int_0^1 a_{t+1}(s_{t+1})Q_{t+1}(s_{t+1})\, ds_{t+1}.$$

A household path is feasible if for all histories of sunspots and $t>0$

$$E_t\left[a_{t+1}Q_{t+1}\right] + \frac{b_t}{1+R_t} = P_{t-1}\left(y_{t-1} - c_{t-1}\right) - T_t - m_t + m_{t-1} + a_t + b_{t-1}, \tag{3}$$

and

$$m_t \ge P_t c_t, \tag{4}$$

together with the initial condition

$$E_0[a_1 Q_1] + \frac{b_0}{1+R_0} = W_{-1} - m_0 - T_0 \tag{5}$$

and the no-Ponzi condition

$$\begin{aligned} a_{t+1} + b_t \ge \underline{A}_{t+1} &:= -P_t - m_t + T_{t+1} \\ &+ E_{t+1} \sum_{j=1}^{\infty} \left\{ \left(\prod_{v=1}^{j} Q_{t+v+1} \right) \left[T_{t+j+1} - P_{t+j} - \max_{\hat{b} \in \mathcal{B}_t} \left[\hat{b} \left(E_{t+j} Q_{t+j+1} - \frac{1}{1+R_{t+j}} \right) \right] \right] \right\}. \end{aligned} \tag{6}$$

Eq. (6) imposes that households cannot borrow more than the present value of working 1 unit of time while consuming nothing, holding no money in every period after t, and maximally exploiting any price discrepancy between government-issued and private securities. This present value is evaluated at the sequence of intertemporal prices $\{Q_t\}_{t=1}^{\infty}$. When $\mathcal{B}_t = \mathbb{R}$, a no-arbitrage condition will ensure $\hat{R}_{t+j} = 1/E_{t+j}Q_{t+j+1} - 1 = R_{t+j}$, making the corresponding term disappear from (6). When limits to household indebtedness against the government are present, we will study equilibria where government securities have a different price than equivalent privately-issued securities, in which case households can profit from the mispricing (at the expense of the government), and the corresponding profits are part of their budget resources.[13] Facing prices $\{P_t, R_t, Q_{t+1}\}_{t=0}^{\infty}$, tax policy $\{T_t\}_{t=0}^{\infty}$, and given initial nominal wealth, a household's problem is to choose $\{c_t, y_t, a_{t+1}, b_t, m_t\}_{t=0}^{\infty}$ to solve

$$\max E_0 \sum_{t=0}^{\infty} \beta^t u(c_t, y_t) \tag{7}$$

[11] That *all* of consumption must be purchased with money is immaterial to our results. It is straightforward to turn our economy into a cash-credit good economy as Lucas and Stokey (1987), by reinterpreting leisure as a credit good and the time endowment as an endowment of goods. It is also straightforward to extend results to including both leisure and credit goods.

[12] In equilibrium, $a_{t+1} \equiv 0$.

[13] Of course, in equilibrium the aggregate profits of the households from this activity are matched by lump-sum taxes that the government has to impose, so that in the aggregate this limited arbitrage opportunity is a zero-sum game.

subject to (3)–(6), and $b_t \in \mathcal{B}_t$. We assume that u is continuously differentiable, that both consumption and leisure are normal goods, and that the following conditions hold:

$$\lim_{c \to 0} u_c(c,y) = \infty \quad \forall\ y > 0, \quad \lim_{y \to 1} u_y(c,y) = -\infty \quad \forall\ c > 0, \tag{8}$$

and

$$\forall\ y > 0\ \exists\ \underline{u}_y(y) > 0 : |u_y(c,y)| > \underline{u}_y(y) \quad \forall\ c \geq 0. \tag{9}$$

Eq. (8) is a standard Inada condition; it will ensure an interior solution to our problem. Eq. (9) imposes that the marginal disutility of labor is bounded away from zero in equilibria in which production is also bounded away from zero.

3. An interest rate policy

In this section, we construct equilibria for an economy in which the government/monetary authority sets an interest rate rule, without imposing limits to household trades with the central bank (i.e., $\mathcal{B}_t = \mathbb{R}$). In particular, suppose the central bank offers to buy or sell any amount of promises to pay \$1 at date $t+1$ for $1/(1+R_t) < 1$ dollars at date t. We assume that nominal interest rates remain strictly positive ($R_t > 0$); this is purely to save notation. In the equilibria featuring runs that are the object of study in this paper, the cash-in-advance constraint will always be binding, even if the policy target is $R_t = 0$.

Using Svensson and Woodford (2005) language, the interest-rate rule is here used as a reaction function: the central bank adopts the interest rate as its instrument, and sets it as a function of everything that is observable up to that point in time. We allow for arbitrary history dependence, so in particular this assumption encompasses Taylor rules that depend on past inflation. In Section 4.2 we discuss the role of this assumption in the broader context of alternatives, and we also explain why it may be particularly appropriate in the wake of the policy of quantitative easing pursued by many central banks across the developed world in recent years.

We suppose that the government sets a “Ricardian” fiscal rule, i.e., a rule that ensures that the present-value budget constraint of the government (and hence the transversality condition of the agents) holds whenever all other competitive equilibrium conditions are met, independent of the price level. We choose such a fiscal policy because we are interested in the set of equilibria that can arise when money is not directly backed by tax revenues, as it happens instead when the fiscal theory of the price level holds. We will specify below a class of fiscal rules that satisfies sufficient conditions for this requirement.

An equilibrium is a sequence $\{P_t, Q_{t+1}, R_t, T_t, C_t, Y_t, A_{t+1}, B_t, M_t\}_{t=0}^{\infty}$ such that $\{C_t, Y_t, A_{t+1}, B_t, M_t\}_{t=0}^{\infty}$ solves the household's problem taking $\{P_t, Q_{t+1}, R_t, T_t\}_{t=0}^{\infty}$ as given, and such that markets clear for all $t \geq 0$:

$$C_t = Y_t - \overline{G} \tag{10}$$

and

$$A_{t+1} = 0. \tag{11}$$

In order for the household problem to have a finite solution, it is necessary that the prices of government and private assets be the same:

$$\hat{R}_t = 1/E_t Q_{t+1} - 1 = R_t. \tag{12}$$

When (12) fails, households can exploit the difference in price to make infinite profits. In addition to (6) and (12), necessary and sufficient conditions from the household optimization problem yield the following conditions for all $t \geq 0$:

$$-\frac{u_y(C_t, Y_t)}{u_c(C_t, Y_t)} = \frac{1}{1+\hat{R}_t}, \tag{13}$$

$$\frac{u_y(C_{t+1}, Y_{t+1})}{u_y(C_t, Y_t)} = \frac{Q_{t+1}(1+\hat{R}_t)}{\beta(1+\hat{R}_{t+1})} \frac{P_{t+1}}{P_t}, \tag{14}$$

$$M_t / P_t = C_t, \tag{15}$$

and the transversality condition[14]

$$\lim_{t \to \infty} E_0 \left[\left(\prod_{j=1}^{t+1} Q_j \right) (A_{t+1} + B_t - \underline{A}_{t+1}) \right] = 0, \tag{16}$$

Substituting (10) and (12) into (13), we obtain

$$-\frac{u_y(C_t, C_t + \overline{G})}{u_c(C_t, C_t + \overline{G})} = \frac{1}{1+R_t}. \tag{17}$$

[14] See Coşar and Green (2015).

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We now turn to considering deterministic equilibria, where the allocation and prices are independent of the realization of the sunspot. In such equilibria, the initial price level, P_0, is not determined. For each initial price P_0, one can use the interest rate rule R_t and Eqs. (1), (2), (10), (14), (15), and (17) to sequentially solve for a *unique* candidate equilibrium allocation and price system.[15] That is, first the fiscal policy rule determines T_0. Given T_0, the interest-rate rule determines R_0, Eq. (17) solves for C_0, Eq. (10) then implies Y_0, and Eq. (15) implies M_0. Finally, Eq. (2) determines B_0. With all time-0 variables now determined, the fiscal policy rule determines T_1, the monetary policy rule determines R_1, which by no arbitrage is equal to $\hat{R}_1$ when $\mathcal{B} = \mathbb{R}$. As in period 0, Eq. (17) solves then for C_1 and Eq. (10) for Y_1. Knowing C_1 and Y_1, Eq. (14) can be solved for P_1, and Eq. (15) for M_1. Eq. (1) then yields B_1, and from there the process continues to period 2 and on.

To verify whether the candidate equilibrium allocation and price system we derived above is an equilibrium, we need only to check that the household transversality and no-Ponzi conditions (6) and (16) hold. To this end, we will restrict fiscal policy to a (broad) class which ensures the policy is Ricardian (Assumption 3); but a necessary step to do so is to ensure that the present value of seigniorage remains finite. This requires either an upper bound on nominal interest rates, so that the opportunity cost of holding money is bounded, or a bound on how valuable money is for transactions, so that households are not willing to forgo infinite resources to acquire money as its opportunity cost becomes arbitrarily large. Formally, we will use either of the following two assumptions:

Assumption 1. $\exists\ \overline{R}: R_t \le \overline{R}$.

or

Assumption 2.

$$\lim_{c \to 0} u(c, y) > -\infty \quad \forall y \ge 0. \tag{18}$$

When either Assumption 1 or Assumption 2 holds, we construct a specific class of Ricardian fiscal policies by positing the following restrictions on taxes:

Assumption 3. There exist finite $\overline{B} > 0, \overline{T} > 0$ and $\alpha \in (0,1)$ such that

- if $B_{t-1} \in [-\overline{B}P_{t-1}, \overline{B}P_{t-1}]$, T_t is unrestricted except $|T_t| \le \overline{T}P_{t-1}$,
- if $B_{t-1} > \overline{B}P_{t-1}$, $T_t \in [\alpha B_{t-1}, B_{t-1}]$, and
- if $B_{t-1} < -\overline{B}P_{t-1}$, $T_t \in [-B_{t-1}, -\alpha B_{t-1}]$.

Essentially, we require that if real debt is neither too high nor too low, taxes may be any function of past information subject only to a uniform bound in real terms. But when real debt exceeds a threshold (in absolute value), taxes cover at least a fraction α of debt, putting the brakes to a debt spiral. As an example, one simple rule that belongs to this general class is $T_t = \alpha B_{t-1}$, with $\alpha \in (0,1)$.[16] We relegate the proof that (6) and (16) hold (and thus the candidate equilibrium is an equilibrium) to the online appendix.

The construction above establishes results that are well known from Sargent and Wallace (1975) and Woodford (2003), and reemphasized by Cochrane (2011). Under an interest rule, the initial price level P_0 is indeterminate, but, once a value of P_0 is specified, there exists a unique deterministic equilibrium allocation and price system. Moreover, in the deterministic equilibrium, in any period in which the nominal rate set by the central bank is low, so is inflation. As an example, if $R_t = (1/\beta) - 1$ for all $t \ge 0$, then inflation is exactly zero in all periods.

When uncertainty is present, sunspot equilibria arise. But, even in that case, a low official interest rate translates into a limit on expected (inverse) inflation. To see this, note that the intratemporal optimization condition (13) and the market clearing condition (10) still hold in a world with sunspots, so Eq. (17) still holds. Thus consumption and labor in each period are pinned down by the interest rate policy. If R_t is constant then consumption and labor are constant. In particular, if $R_t \equiv (1/\beta) - 1$ in all periods, Eq. (14) simplifies to

$$E_t \frac{P_t}{P_{t+1}} = 1. \tag{19}$$

The expected real value of a dollar remains constant into the future. Furthermore, if we assume a bound ϵ on how fast the price level can drop (i.e., we impose $P_t / P_{t+1} < 1/\epsilon$ almost surely $\forall t$), then the law of large numbers will apply, and average

[15] The Inada condition and the assumptions of normal goods ensure that an interior solution can be found and that (17) is strictly monotone in C_t. In our analysis, we do not rule out explosive paths, for the reasons highlighted in Cochrane (2011).

[16] We rely on Assumption 3 because it is an explicit characterization of policies that depend only on past information and are Ricardian. Our results hold for other Ricardian policies that are measurable to past information.

inverse inflation over long horizons will be 0:

$$\lim_{T\to\infty} \frac{1}{T}\sum_{s=1}^{T} \frac{P_s}{P_{s+1}} = 1 \text{ almost surely.} \tag{20}$$

In the next section, we show that a very different type of equilibrium emerges when households are not allowed to borrow unlimited funds from the central bank. In this equilibrium, a low interest rate set by the central bank is accompanied by high expected inflation from the outset, and private-market interest rates diverge from the policy rate.

4. Limits to central bank lending

Suppose now we impose the additional constraint on the households that $B_t \geq 0$, $t \geq 0$: households are not allowed to borrow from the government/central bank (or, equivalently, they are allowed to borrow from the central bank only by posting government bonds as collateral). That the borrowing limit is precisely zero is not central to our analysis, but simplifies exposition somewhat. In this section, we construct additional deterministic equilibria which do not exist when $\mathcal{B}_t = \mathbb{R}$.

With the no-borrowing limit we just imposed, the official rate R_t only becomes a lower bound for the private-sector rate $\hat{R}_t$. When households are at the borrowing limit with the central bank, private nominal interest rates may exceed the official rate. The no-arbitrage condition (12) becomes

$$\hat{R}_t = 1/E_t Q_{t+1} - 1 \geq R_t. \tag{21}$$

All other equilibrium conditions remain the same, except that the private rate $\hat{R}_t$ replaces the government rate R_t in Eq. (17):

$$-\frac{u_y(C_t, C_t+\overline{G})}{u_c(C_t, C_t+\overline{G})} = \frac{1}{1+\hat{R}_t}. \tag{22}$$

The allocation of Section 3 remains part of an equilibrium even when the central bank limits its lending, provided that households have positive bond holdings in all periods. Define $\hat{c}(R)$ as the consumption level that solves Eq. (17) as a function of the nominal interest rate (the opportunity cost of holding money). In the online appendix, we prove that the following conditions are sufficient to ensure that the deterministic equilibrium that features no runs has positive bond holdings in all periods:

$$T_0 < W_{-1}, \tag{23}$$

$$T_0 < W_{-1} - \hat{c}(R_0)P_0, \tag{24}$$

and[17]

$$\frac{T_t}{P_{t-1}} < \overline{G} + \frac{B_{t-1}}{P_{t-1}} + \hat{c}(R_{t-1}) - \frac{\beta\hat{c}(R_t)(1+R_t)\hat{u}_y(R_t)}{\hat{u}_y(R_{t-1})}, \tag{25}$$

where $\hat{u}_y(R) := u_y(\hat{c}(R), \overline{G} + \hat{c}(R))$ is the marginal utility of leisure evaluated at the equilibrium choice when the interest rate (in the private market) is R.

The same conditions also ensure the existence of sunspot equilibria with positive debt. We will thus assume that these conditions are met.

4.1. Additional equilibria: a single, deterministic run

The simplest equilibrium that may arise when a limit to private indebtedness is introduced is a deterministic run, where $B_s = 0$ for a single date $s > 0$. In the case of the German Reichsbank, this is an equilibrium in which all of the government debt is monetized in period s. Under the QE interpretation, this is an equilibrium in which households demand enough cash (and, in a richer model, banks expand their deposits so much) that all of the excess reserves are converted into cash (and required reserves).

The conditions under which such a simple equilibrium exists are stringent. This is not surprising: it is true in all models of runs. To use a fixed exchange-rate regime as an example, equilibria in which a fixed exchange rate collapses at a perfectly anticipated time exist only in very specific circumstances. In the next subsection, we will extend the analysis to probabilistic runs, where the date at which inflationary expectations take off and a run occurs is not perfectly known ahead of time. Such equilibria exist under much more general conditions. The preferences for which we can generally prove that a deterministic run occurs are incompatible with Assumption 2. We thus need to assume that Assumption 1 holds, i.e., that the nominal interest rate set by the central bank remains bounded. We furthermore need the following:

[17] Under either Assumption 1 or Assumption 2, the online appendix shows an example of a fiscal rule that satisfies (25) and Assumption 3.

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Assumption 4. Define

$$\overline{u}_y := \max_{R \in [0,\overline{R}]} \hat{c}(R)(1+R)|\hat{u}_y(R)|. \tag{26}$$

We assume that fiscal policy satisfies the following stronger version of (25):

$$\frac{T_t}{P_{t-1}} < \overline{G} + \frac{B_{t-1}}{P_{t-1}} + \frac{M_{t-1}}{P_{t-1}} - \frac{\beta \overline{u}_y}{\underline{u}_y(\overline{G})}, \tag{27}$$

where $\underline{u}_y(\overline{G})$ is defined in (9).

Eq. (25) guaranteed that in each period there are positive bonds/excess reserves that can be converted into money and initiate a speculative run. The stronger condition (27) ensures that, *after* a period in which a run occurred and thus previous government debt was monetized, there are enough new bonds (or the monetary base is sufficiently large) that the economy can return to a path where households hold positive amounts of government debt and Eq. (14) holds.[18] This is a sufficient condition that ensures that the run can last just one period: otherwise, households may not be able to acquire enough money to bring consumption back to the equilibrium that features no run.[19]

Proposition 1. *Let* $\{P_t, Q_{t+1}, R_t, T_t, C_t, Y_t, A_{t+1}, B_t, M_t\}_{t=0}^{s-1}$ *be determined as in the equilibrium of Section 3, with* P_0 *satisfying (24), and let fiscal policy satisfy Assumption 4. A necessary and sufficient condition for the existence of a different (deterministic) equilibrium in which* $B_s = 0$ *and* $\hat{R}_s > R_s$ *is that the following equation admits a solution for* $\hat{R}_s > R_s$:

$$\beta \hat{u}_y\left(\hat{R}_s\right)\left(1+\hat{R}_s\right)\hat{c}\left(\hat{R}_s\right)\left(\frac{P_{s-1}}{M_{s-1}+B_{s-1}+P_{s-1}\overline{G}-T_s}\right) = \hat{u}_y(R_{s-1}). \tag{28}$$

A sufficient condition (based on preferences alone) for (28) to have a solution with $\hat{R}_s > R_s$ *is*

$$\lim_{R\to\infty} |\hat{u}_y(R)|(1+R)\hat{c}(R) \to \infty. \tag{29}$$

Proof. The proof works by construction. Starting from an arbitrary price level P_0 that satisfies (24), the equilibrium allocation, price system, and government policy are solved as in Section 3 up to period $s-1$. Specifically, we use the interest rate rule R_t and the fiscal policy rule with Eqs. (10), (14), (15), and (17) to sequentially solve for the unique candidate equilibrium allocation and price system.

In period s, in order for $\hat{R}_s > R_s$ to be an equilibrium, the constraint $B_s \geq 0$ must be binding, which implies

$$\frac{M_{s-1}+B_{s-1}}{P_{s-1}} + \overline{G} = \frac{T_s}{P_{s-1}} + \hat{c}\left(\hat{R}_s\right)\frac{P_s}{P_{s-1}}. \tag{30}$$

Furthermore, Eqs. (14) and (22) require

$$\beta\left(1+\hat{R}_s\right)\hat{u}_y\left(\hat{R}_s\right)\frac{P_{s-1}}{P_s} = \hat{u}_y(R_{s-1}). \tag{31}$$

Substituting (30) into (31), we obtain (28), which is a single equation to be solved for $\hat{R}_s$. If this equation does not admit a solution for $\hat{R}_s > R_s$, then it is impossible to satisfy all of the necessary conditions for an equilibrium with $B_s = 0$. If a solution exists, then we can retrieve consumption in period s as $C_s = \hat{c}(\hat{R}_s)$ (the unique solution that satisfies Eq. (22)), and hence (by market clearing) $Y_s = C_s + \overline{G}$. We can then solve Eq. (30) for the candidate equilibrium level of P_s. Eq. (25) ensures that the solution for P_s is strictly positive.

From period $s+1$ onwards, the allocation and price system is once again uniquely determined (sequentially) by the interest rate rule R_t, the fiscal policy rule, and Eqs. (10), (14), (15), and (17). Eq. (27) ensures that the resulting sequence for government debt is strictly positive. Once again, the proof that (6) and (16) hold is relegated to the general proof in the online appendix.

Finally, to verify the sufficient condition (29), set $\hat{R}_s = R_s$. Eqs. (14) and (25) imply

$$\beta\left|\hat{u}_y(R_s)\right|(1+R_s)\hat{c}(R_s)\left(\frac{P_{s-1}}{M_{s-1}+B_{s-1}+P_{s-1}\overline{G}-T_s}\right) < |\hat{u}_y(R_{s-1})|. \tag{32}$$

Since $|\hat{u}_y(R)|(1+R)\hat{c}(R)$ is a continuous function of R, when Eq. (29) holds, Eq. (32) ensures the existence of a solution of (28) with $\hat{R}_s > R_s$. □

[18] The online appendix shows an example of a fiscal rule that satisfies (27) and Assumption 3.

[19] For preferences such that $\hat{c}(R)(1+R)|\hat{u}_y(R)|$ is monotonically increasing in R, ensuring that enough nominal wealth is available after a run begins is necessary for the run to take place; for these preferences, Eqs. (13) and (14) imply an upward-sloping nominal money demand as a function of the private-market interest rate prevailing in the period after the run begins. In this case, if households do not have enough nominal wealth to acquire money at the rate set by the central bank in the period after the run begins, increasing $\hat{R}$ above R would not help in restoring equilibrium. As we will discuss when we present stochastic runs in the next subsection, the empirically relevant case is one in which Assumption 2 applies and this issue does not arise.

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To be concrete, we consider a numerical example. In the example, the monetary authority sets the interest rate at an unconditional constant: $R_t = (1/\beta) - 1$, where $\beta = 1/1.01$.[20] Given our parametric assumptions, one equilibrium of this economy is a steady state: In each period $t \geq 0$, $P_t = 1$, $C_t = M_t = .96$, $Y_t = 1.06$ and $B_t = 1.5$.[21]

Next suppose households face a restriction that $B_t \geq 0$ for all $t \geq 0$. Then, Figs. 2–4 describe the unfolding of the run. The basic intuition behind a run is simple: when the run occurs, all government debt is converted into money; this largely increases the money supply. When all other households are expected not to roll over their debt, each household expects thus a high money supply and high resulting inflation; in response to this expectation, the optimal strategy is not to roll over nominal debt, validating the run.

To go beyond this basic intuition and understand why a perfectly anticipated run requires specific assumptions about preferences, we inspect the evolution of the run in greater detail. First, notice that, if a run occurs, the private-sector interest rate $\hat{R}_t$ must be greater than the interest rate set by the central bank, which is constant at $1/\beta - 1$; in our example, this occurs in period 2, as shown in the left panel of Fig. 2. The intratemporal optimality condition (22) implies that consumption decreases in period 2, when the run occurs (right panel of Fig. 2).

With consumption down and the money supply up, the price level must jump up so that the (binding) cash-in-advance constraint holds, as shown by the left panel of Fig. 3. Whether such a candidate allocation can be supported as an equilibrium depends on whether these changes can be made consistent with the household Euler equations for leisure and consumption, which are respectively (14) and

$$\frac{u_c(C_{t+1}, Y_{t+1})}{u_c(C_t, Y_t)} = \frac{1}{\beta(1+\hat{R}_t)} \frac{P_{t+1}}{P_t}. \tag{34}$$

Specifically, in order to have a perfectly anticipated run in period 2, and not before, it must be the case that households are willing to lend to the government in period 1 (or to keep excess reserves deposited at the central bank, depending on the interpretation) even though the nominal interest rate by the central bank is constant and expected inflation between period 1 and period 2 is high. Since households expect a consumption drop between periods 1 and 2, this can be the case, but only if either the drop in consumption (and, by market clearing, in the labor supply) is very steep or the intertemporal elasticity of substitution of consumption is sufficiently low. Eq. (22) implies that the consumption drop is steeper the less curvature there is in the marginal disutility of labor and in the marginal utility of consumption. So, less curvature in $u_y(c, c+\overline{G})$ unambiguously helps in satisfying Eq. (34). Less curvature in $u_c(c, c+\overline{G})$ has an ambiguous effect, since (for given $\hat{R}_s$) it creates a bigger drop in consumption, but it also implies a greater intertemporal elasticity of substitution. The second effect turns out to be the relevant one, so that a perfectly anticipated run can happen when the curvature is high and hence the function $\hat{c}$ is not very responsive to R. From these observations, we can thus understand the role of Eq. (29). We can also understand why a run can happen under much weaker assumptions if it occurs with probability smaller than one, as described in the next subsection: in this case, the potentially negative effect of a run on the households' willingness to save between periods 1 and 2 is tempered by the lower probability of the occurrence. In the limit, as the probability of a run goes to 0, households are content to save at the rate $1/\beta - 1$ between periods 1 and 2 when the no-run allocation remains at the steady state throughout.

Next, we consider the other intertemporal choice that households face in their decision to save between periods 1 and 2, i.e., their labor supply. Because of the cash-in-advance timing, this decision is related to the household labor supply in periods 0 and 1, as shown by Eq. (14). Since the allocation and inflation are at the no-run steady state values in these two periods, the relevant Euler equation for leisure is automatically satisfied. For this reason, the intertemporal elasticity of substitution of leisure does not play the same role as the one of consumption in determining whether a perfectly anticipated run can occur.

Having discussed the economic forces that lead households to save between periods 0 and 1, we next consider the elements that pertain to the private-market interest rate between periods 1 and 2, in the period of the run. This time, it is simpler to start from the Euler equation for labor, Eq. (14). The relevant margin of choice for households is their labor supply in period 1 (paid in period 2) vs. period 2. Here, it is straightforward to see why households optimally choose not to invest in government bonds in period 2 at the nominal rate $1/\beta - 1$. First, the nominal wage (which is equal to the price level) increases from period 1 to period 2, which yields an incentive to postpone labor when the nominal interest rate does not adjust correspondingly. Second, the equilibrium features actually a lower labor supply (which tracks consumption) in period 2 than in period 1, providing a further incentive not to save in period 1 and to postpone work. Both of these channels imply that the interest rate offered by the government within the equilibrium allocation is too low for households to be willing to lend to the government, and that the private-market interest rate that justifies the labor decision is instead higher. Similarly, on the consumption side (where the relevant margin is once again shifted one period forward), households look forward to

[20] We set $u(c_t, y_t) = (c^{1-\sigma}/(1-\sigma)) - y^{\psi}$, with $\sigma = 3$ and $\psi = 1.1$, and let $\overline{G} = 0.1$. With these parameters, Eq. (27) becomes

$$T_t < B_{t-1} + M_{t-1} - 1.12P_{t-1}. \tag{33}$$

We assume $T_t = 0.5(B_{t-1} + M_{t-1}) - 1.12P_{t-1}$. This satisfies (33) whenever $B_{t-1} + M_{t-1} > 0$, which holds throughout the example. We also set $P_0 = 1$ and $W_{-1} = 2.57$.

[21] There are other deterministic equilibria, indexed by the initial price level P_0, but all of them share the same level of consumption, output, and real money balances.

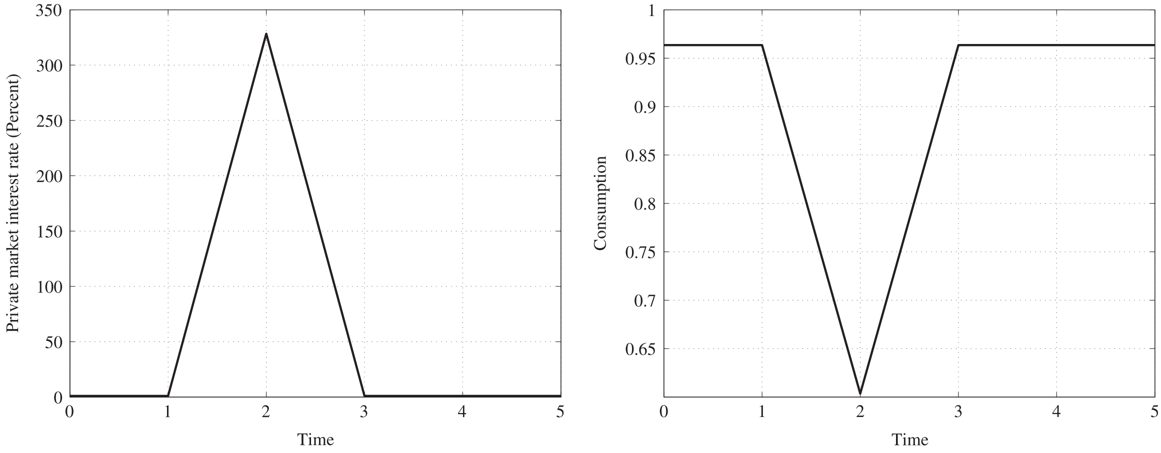

Fig. 2. Private-market interest rate (left panel) and consumption (right panel) in an equilibrium featuring a run in period 2 only.

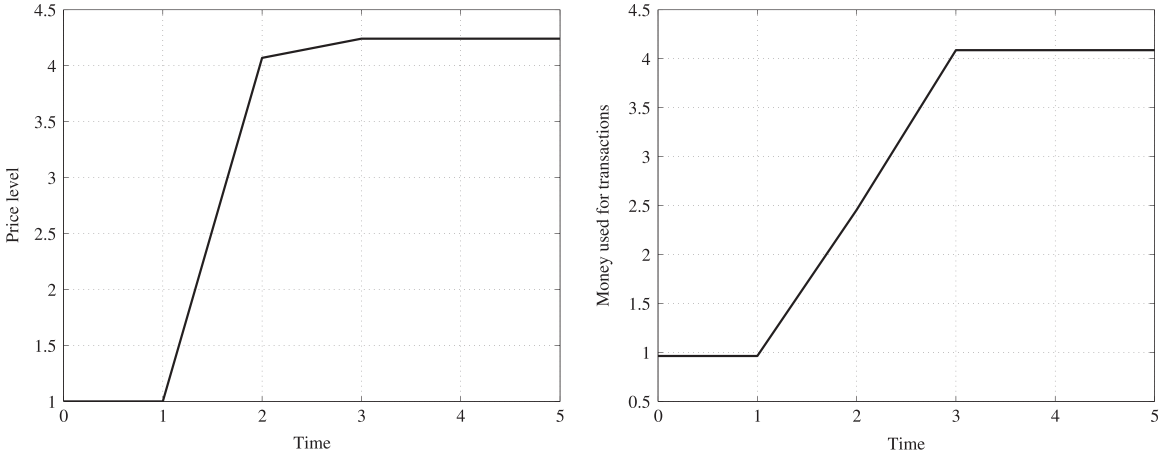

Fig. 3. Prices (left panel) and money used for transactions (right panel) in an equilibrium featuring a run in period 2 only.

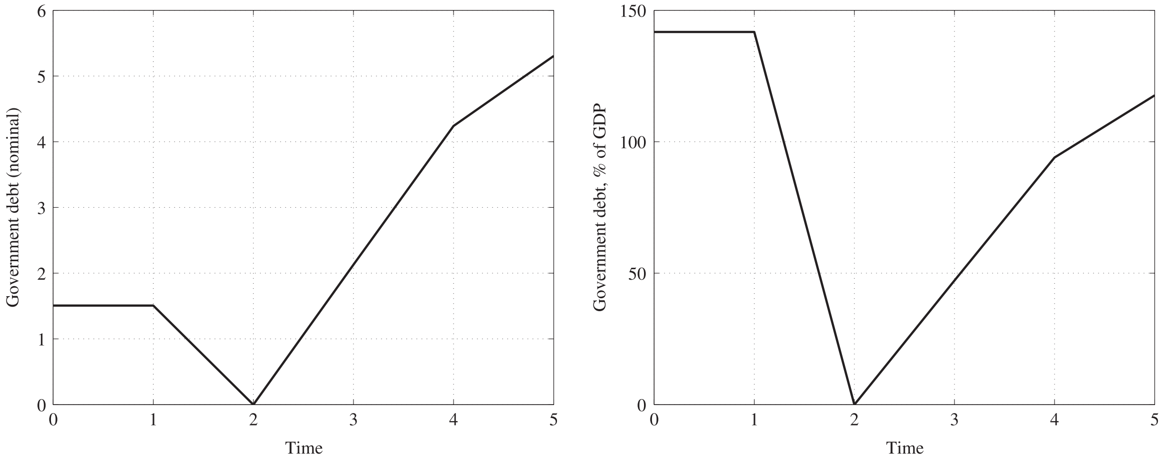

Fig. 4. Government debt in an equilibrium featuring a run in period 2 only: nominal (left panel) and as a ratio of GDP (right panel).

an increase in consumption between periods 2 and 3, and hence they require a higher real interest rate to be willing to save than the one offered by the government. This is particularly true because further inflation occurs between periods 2 and 3, as we establish next, in our discussion of how the run ends.

After the run ends, households resume lending to the government at the rate $R_3 = 1/\beta - 1$ in period 3. With a fixed nominal interest rate, inflation between period 2 and 3 must adjust so that households find it optimal to increase their labor supply between the crisis period 2 and the return to normalcy in period 3. By Eq. (14), this requires further inflation between periods 2 and 3. The increase in both prices and production (and consumption) between periods 2 and 3 implies that money supply must also grow. Since the crisis wiped out government debt, households cannot acquire this additional money by selling government debt. If the run is to last only a single period, fiscal policy must generate enough new nominal liabilities at the beginning of period 3, as implied by Assumption 4; this is achieved through a tax cut. From that point onward, output and consumption return to their pre-run steady state, while government debt (in real terms) converges back to the steady state gradually.

By repeating the steps outlined in Section 4.1, it is easy to construct equilibria in which runs occur repeatedly, and it is also possible to construct equilibria in which runs last for more than one period. The conditions under which such equilibria exist are similar to those for a single run (in particular, Assumptions 1, 3, and 4 are sufficient conditions).

The example that we presented is extreme: the price level jumps by a factor of 4 in a single period. The total size of the jump reflects the fact that, before the run, M_t is substantially smaller than B_t. This is currently the case for many CBs around the world, for which the size of excess reserves held by the banking sector (the fuel for a potential run) is much larger than currency and required reserves (the part of the monetary base that the private sector uses for transaction purposes). In practice, however, a run would not unfold in a single instant: our model lacks any of the information frictions and transaction costs that would prevent all private agents to perfectly coordinate the timing of their attack. In such a richer model, a run could occur more gradually, with some agents moving earlier and others following their lead.

4.2. Stochastic runs

While deterministic runs are useful in illustrating the mechanism behind our result, they require stringent assumptions. Assumption 1 is violated if the central bank follows a Taylor rule, whereby nominal interest rates respond to inflation without bounds. Preferences that satisfy Eq. (29) are empirically implausible, since they imply that the government could extract infinite seigniorage revenues by setting nominal interest rates (the price of cash goods) arbitrarily high. The experience of countries that witnessed hyperinflations suggests that this is not the case: a Laffer curve seems to be present for the inflation tax, as implied by preferences that satisfy Assumption 2 instead.[22]

In this subsection, we consider stochastic equilibria, where runs can emerge with probability less than 1. These sunspot equilibria emerge under much more general conditions. These equilibria are still very different from those identified by Sargent and Wallace (1975).

Consider first the Sargent–Wallace setup, where $\mathcal{B}=\mathbb{R}$ and no runs can occur. In this case, the nominal interest rate is closely related to expected (inverse) inflation, so that setting the nominal interest rate still allows the central bank a considerable degree of control, at least over long periods of time. We can construct sunspot equilibria recursively as follows. For any arbitrary initial price P_0, the variables R_0, T_0, C_0, Y_0, M_0, and B_0 are determined as in Section 3. The time-0 variables and the policy rules determine R_1 and T_1, also as in Section 3, which then pin down C_1 and Y_1; this implies that C_1 and Y_1 are known as of period 0.[23] In an equilibrium with no runs, we know that $\hat{R}_1=R_1$. Substituting this into (14), rearranging and taking expected values we obtain

$$E_0\frac{P_0}{P_1}=\frac{u_y(C_0,Y_0)}{\beta u_y(C_1,Y_1)(1+R_1)}. \tag{35}$$

We can then pick P_1 as an arbitrary function of the sunspot s_1, subject to the single restriction (35) on its expected value. Given the realization of s_1 and thus P_1, Eq. (15) determines M_1, Eq. (1) yields B_1, and the process can be repeated for period 2.

Provided that either Assumption 1 or 2 hold, the online appendix proves that the transversality and no-Ponzi conditions are satisfied for the sequences that we constructed: as discussed in Cochrane (2011), in this model only fiscal policy can provide a boundary condition to rule out some of these arbitrary paths.[24]

While sunspot equilibria imply that inflation is indeterminate, equilibria that feature no runs still display remarkable similarities across each other. As an example, suppose that monetary policy sets $R_t \equiv 1/\beta-1$ unconditionally. It is straightforward to verify that Eq. (17) implies a constant allocation, and that (14) implies (19): the expected real value of a dollar remains constant. Eq. (19) and the assumption of a uniform bound on P_t/P_{t+1} in turn imply (20).

The tight relationship between nominal interest rates and expected inverse inflation is lost in equilibria that feature runs, and the dangers from relying purely on the nominal interest rate as a policy instrument are correspondingly more acute. To see this, we reintroduce the bound on household indebtedness with the central bank, so that they are limited to $B_t \geq 0$.

Rather than Assumption 4, which might appear overly strong, we rely here on a weaker sufficient condition for fiscal policy:

[22] Of course, both Assumption 1 and (29) are sufficient, not necessary conditions, so there are functions and parameter values for which deterministic equilibria may exist even when they are violated.

[23] We assume that the monetary and fiscal authorities follow deterministic rules; this is immaterial to our results.

[24] Notice that uniqueness results based on the failure of both Assumptions 1 and 2 relate to fiscal policy: some sunspot paths can be ruled out because seigniorage revenues become infinite, making it impossible for fiscal policy to be Ricardian.

Assumption 5.

- Eq. (23) holds for period 0 and Eq. (25) holds in all periods in which $B_{t-1} > 0$;
- When $B_{t-1} = 0$, taxes satisfy

$$\frac{T_t}{P_{t-1}} < \overline{G} + \frac{M_{t-1}}{P_{t-1}}.$$

The first requirement of Assumption 5 implies that, if debt was strictly positive in period $t-1$ (and thus no run took place), there exists a continuation equilibrium where the debt constraint is not binding into the indefinite future. When $B_{t-1} = 0$, we impose the weaker requirement that taxes do not exceed the nominal assets in the hands of the households: if they did, the borrowing constraint would make it impossible for households to meet their tax obligations.

We can now prove the following:

Proposition 2. *Let* $\{P_t, Q_{t+1}, R_t, T_t, C_t, Y_t, A_{t+1}, B_t, M_t\}_{t=0}^{s-1}$ *be determined as in the equilibrium of Section 3, with* P_0 *satisfying (24). Let Assumptions 2, 3, and 5 hold. Then, given any period s, there exists* $\overline{\phi}_s > 0$ *such that there are equilibria in which* $B_s = 0$ *and* $\hat{R}_s > R_s$ *with any probability* $\phi \in [0, \overline{\phi}_s]$.

Proof. Once again, we prove this by construction. We display an equilibrium where a run occurs in period s with probability ϕ. Starting from an arbitrary initial price level P_0, we construct recursively a deterministic allocation and price system up to period $s-1$ as we did in Section 4.1. For period s, we consider an equilibrium with just two realizations of the allocation and price level: with probability ϕ, the price level is P_s^H and a run occurs ($\hat{R}_s^H > R_s$), and with probability $1-\phi$ the price level is P_s^L and the private nominal interest rate coincides with the public one: $\hat{R}_s^L = R_s$. In order for $\hat{R}_s^H > R_s$ to be an equilibrium, the constraint $B_s \geq 0$ must be binding, which implies

$$\frac{M_{s-1} + B_{s-1}}{P_{s-1}} + \overline{G} = \frac{T_s}{P_{s-1}} + \hat{c}\left(\hat{R}_s^H\right)\frac{P_s^H}{P_{s-1}}. \tag{36}$$

Given any arbitrary value $\hat{R}_s^H > R_s$, and given the predetermined time-$s-1$ variables and the fiscal policy rule for T_s, Eq. (36) can be solved for P_s^H/P_{s-1}, the level of inflation that will occur if a run on the interest rate peg materializes in period s. As was the case in Section 4.1, since $\hat{c}$ is a decreasing function and taxes satisfy (25), inflation in the event of a run will necessarily be strictly greater than inflation in the equilibrium in which no run can take place.

To determine P_s^L/P_{s-1}, we rely on the household Euler Eq. (14). Rearranging terms and taking the expected value as of period $s-1$, we obtain

$$\beta\left[\phi\hat{u}_y\left(\hat{R}_s^H\right)\left(1+\hat{R}_s^H\right)\frac{P_{s-1}}{P_s^H} + (1-\phi)\hat{u}_y(R_s)(1+R_s)\frac{P_{s-1}}{P_s^L}\right] = \hat{u}_y(R_{s-1}). \tag{37}$$

Generically, this equation can be solved for P_s^L/P_{s-1}. However, we need to ensure that the solution is nonnegative, and that it entails nonnegative bond holdings, i.e., that

$$M_{s-1} + B_{s-1} + P_{s-1}\overline{G} \geq \frac{T_s}{P_{s-1}} + \hat{c}(R_s)\frac{P_s^L}{P_{s-1}} \tag{38}$$

A sufficient condition for both is that ϕ be sufficiently small.[25]

If $\hat{u}_y$ does not decline too fast with R, then Eq. (37) will imply that P_s^L/P_{s-1} is lower than in the deterministic equilibrium with no runs. Because of this, the possibility of a run may cause the central bank to *under*shoot inflation while the run is not occurring, further undermining inflation stability.

From period s onwards, the characterization of the equilibrium proceeds again deterministically and recursively, separately for the branch that follows P_s^H and P_s^L. For the branch that follows P_s^L, $B_s > 0$, and so Assumption 5 ensures that there exists a deterministic equilibrium path constructed as in Section 4.1 where debt always remains positive. Following the occurrence of the run, we first check whether continuation of the run in period $s+1$ can be part of an equilibrium path. Combining Eqs. (1), (13), and (14), a continuation of the run into period $s+1$ requires

$$\frac{u_c(C_{s+1}^H, C_{s+1}^H + \overline{G})C_{s+1}^H}{P_s^H\overline{G} + M_s^H - T_{s+1}} = -\frac{C_s^H u_y(C_s^H, C_s^H + \overline{G})}{M_s^H}. \tag{39}$$

If (39) admits a solution in C_{s+1}^H for a value smaller than $\hat{c}(R_{s+1})$, then the run will continue in period $s+1$. Otherwise, if the left-hand side remains smaller than the right-hand side for all values of consumption in $(0, \hat{c}(R_{s+1})]$,[26] the run ends, we set $C_{s+1}^H = \hat{c}(R_{s+1})$ and solve for the allocation as in Section 4.1; the resulting solution will then necessarily feature $M_{s+1}^H < P_s^H\overline{G} + M_s^H - T_{s+1}$, which confirms that debt turns strictly positive and that the run is over. The same procedure

[25] Note that, as $\phi \to 0$, P_s^L/P_{s-1} converges to the inflation in the deterministic equilibrium with no runs, where (25) guarantees that (38) holds.

[26] The role of Assumption 2 is to rule out the possibility that the left-hand side is larger than the right-hand side on the entire interval.

can be followed to determine the allocation in all subsequent periods. Either the run will end in finite time, if enough nominal government liabilities are eventually available, or it will continue for ever, in which case inflation is no longer determined by the interest rate set by the central bank, but rather by the money supply. Finally, the online appendix proves that the transversality and no-Ponzi conditions are satisfied for the sequences that we constructed. □

Contrary to what happens in the sunspot equilibria of Sargent and Wallace (1975), in equilibria featuring stochastic runs, even when the official interest R_t is constant, the levels of consumption and labor are not constant, because the effective interest rate $\hat{R}_t$ that is relevant for the households is not constant. Further, when $R_t=(1/\beta)-1$, it is no longer the case that on average $P_t/P_{t+1}=1$. Setting a low nominal rate no longer guarantees low average real depreciation of the currency.

We illustrate stochastic runs with a numerical example. In this example, fiscal policy does not ever cut taxes enough for the run to end; once a run takes place, it becomes permanent, and real money balances vanish over time.[27] As in Section 4.1, we retain the assumption that the monetary authority sets the interest rate at an unconditional constant: $R_t=(1/\beta)-1$. Before a run occurs, we assume that taxes are set as follows:

$$T_t=0.05B_{t-1}-0.01P_{t-1}.$$

After the run, we assume that the government sets a balanced budget ($T_t=P_{t-1}\overline{G}$), which (with no debt) implies that the money supply is constant. We initialize the economy with a level of W_{-1} such that the economy is in steady state with $P=1$. We consider a run that occurs with 10% probability in period 2, and such that $\hat{R}_2=3\%$. Fig. 5 shows the evolution of consumption and the price level after a run.

In this equilibrium, following a run, monetary policy effectively corresponds to a constant money supply rule. As is well known,[28] without fiscal backing such a rule admits self-fulfilling inflations where real balances vanish over time. The initial conditions determined by the size of the run select one such self-fulfilling inflation.

Notice that, along this path, the fiscal/monetary authorities remain ready to sell government bonds at the interest rate $1/\beta-1$; however, since inflation is positive (and accelerating) and consumption is decreasing, this rate is too low for households to be willing to hold bonds, and they remain at a corner in their bond-holding choice.

In the simple examples above, we assumed that the central bank sets an unconditional interest rate peg. However, our results hold even when interest rates exhibit arbitrary dependence on the past; in particular, Taylor rules that depend on past inflation fit our framework well.[29]

Our results would of course change if the interest rate is not simply *set* by the central bank, by standing ready to trade at the given rate, but is instead simply a *target* to be attained through different, potentially more complicated (and unspecified) rules. Following Svensson and Woodford (2005), central banks in the past may have adopted interest-rate rules as "targeting rules," but may have then implemented those rules in different ways.[30] Indeed, *until 2008*, most central banks did not set a fixed rate at which they were willing to trade with the private sector, but rather they relied on controlling the monetary base day to day through open-market operations to achieve their target; this might be the reason we have not observed any of the runs described here in the recent past.

If the interest-rate rules adopted by central banks in the past were mere targeting rules, and not true reaction functions, our analysis still provides several new insights:

- A more complete specification of the low-level reaction function is essential to understand how central banks successfully kept inflation in check and prevented runs. Most likely, this did not involve passively supplying the money required to achieve the interest rate target, which would be equivalent to the strategies described above, but would instead be closer to the "twin-pillar doctrine," as discussed in Lucas (2007), and possibly explicit fiscal backing as in Wallace (1981) or Del Negro and Sims (2015, this issue) to prevent the disappearance of money altogether.
- The advent of quantitative easing may have created a danger of runs that was not previously present. Since 2008, the large amount of excess reserves held by commercial banks has implied that the chief instrument to attain the interest-rate target is the rate paid by the central bank on excess reserves. Paying interest on reserves is also an essential element of the planned exit strategy, while central banks gradually reduce the size of their balance sheet (see, for instance, Bernanke, 2012). The strategy of paying interest on reserves is well captured by our Section 4.1 if we simply reinterpret B_t as the central bank's own interest-bearing debt (excess reserves), rather than the entire stock of government debt. By relying on interest-on-reserves as its primary tool to achieve the interest-rate target, a central bank stands ready to exchange cash for reserves at the given interest rate (which can be a function of anything that the central bank has observed in the past): this is precisely the strategy that creates the possibility of a run of the type that we discussed.

[27] We set $\beta=1/1.01$, $u(c_t,y_t)=(c^{1-\sigma}/(1-\sigma))-y^{\psi}$, with $\sigma=.5$ and $\psi=1.1$, and $\overline{G}=.1$. Compared with Section (4.1), the choice of $\sigma<1$ implies that Assumption 2 now holds.

[28] See, for example, Wallace (1981).

[29] In the case of "active" Taylor rules, Assumption 1 (that nominal interest rates are bounded) is violated, which implies that a deterministic run may not exist, but runs that occur with smaller probability will.

[30] As an example, Atkeson et al. (2010), following the methods in Bassetto (2005), devise more sophisticated strategies to achieve unique implementation by reverting to money supply rules when the inflation rate deviates from its target. But money supply rules may also be subject to multiple equilibria. Alternatively, uniqueness can be attained by strategies where currency is explicitly backed by fiscal revenues, as in the fiscal theory of the price level.

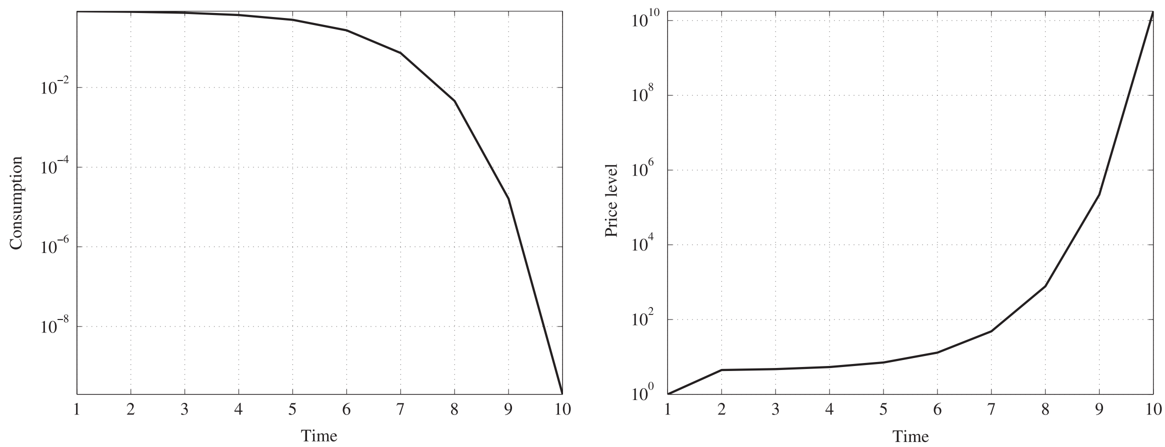

Fig. 5. Consumption (left panel) and prices (right panel) in the event that a run with money kept constant after the run. The run starts in period 2 and becomes permanent.

- The Federal Reserve System faced exit from a situation of large excess reserves held by the banking sector once before, in the 1940s. Eichengreen and Garber (1991) argue that the Fed controlled liquidity during those years by changing reserve requirements, which then allowed it to stabilize inflation expectations and therefore support stable interest rates. To the best of our knowledge, changes in reserve requirements have not been cited as one of the tools that will be adopted during the exit from quantitative easing. Our analysis suggests instead that they would be an essential tool in preventing runs on the interest rate set for excess reserves and the associated inflationary consequences.

5. Debt and the severity of runs

In characterizing the equilibria of Section 3, where bounds to open-market operations are disregarded, the depth of the bond market targeted by the central bank plays no role. This changes when bounds are introduced. We explore here two ways in which this may be relevant for the conduct of monetary policy.

The presence of runs generates a new channel of interaction between monetary and fiscal policy. When we restrict discussion to Ricardian fiscal policies and equilibria without borrowing limits, fiscal policy is irrelevant in determining equilibrium consumption and labor levels. (In fact, this is the entire point of Ricardian equivalence.) When limits are present and the equilibrium features runs, the consequences of a run will be more severe, the greater the pool of bonds that is available to be monetized. As an example, consider the run equilibrium of Section 4.1, but with a different tax policy. In particular, instead of $T_t = 0.5(B_{t-1}+M_{t-1})-1.12P_{t-1}$, let $T_t = 0.6(B_{t-1}+M_{t-1})-1.12P_{t-1}$. This leaves consumption and output unchanged in the no-run equilibrium, but decreases the steady state level of debt from 1.5 to 1.09. Now, at date s (when the run occurs), $B_s=0$ (as before), but since B_{s-1} is now lower, there is less debt to convert into money, and thus the money rises less from period $s-1$ to period s. In this new example, P_s rises from 1 to 3.08 (instead of rising to 4.08), M_s rises from 0.96 to 2.04 (instead of rising to 2.46), C_s falls from 0.96 to 0.66 (instead of falling to $C_s = 0.6$), and $\hat{R}_s$ rises to 2.22 instead of rising to 3.28. Overall, that the increase in the money supply is smaller due to the smaller date $s-1$ debt causes smaller *real* effects (on consumption and output) from the run.

Rather than relying on the fiscal authorities to restrict the pool of available bonds, an alternative strategy for the central bank to mitigate the consequences of a run is to peg rates on only a subset of the bonds. In practice, this is a relevant scenario for at least three reasons:

1. In the real world, there is long-term debt, whose price is not directly targeted by the central bank.
2. It is unlikely that the central bank would be willing to monetize the entire amount of government debt; rather, the bound after which a CB would stop accommodating a run is likely to be tighter.
3. On the contrary, it is harder for the central bank to stop accommodating a run on excess reserves, that represent its own obligations. For this reason, a policy of quantitative easing may affect the severity of a run by altering the amount of resources that households can convert on demand into money to be used for transactions.

Here, we consider the case in which there are two types of bonds, "red" bonds and "blue" bonds, both with one-period maturity, whose only difference stems from their treatment by the central bank.[31] We assume that, when asset markets open, the central bank sets the interest rate on red bonds, being willing to purchase or sell them at a rate R_t (which may

[31] This is helpful in keeping notation simple, but our analysis would apply equally well to debt of different maturities, where the central bank sets the interest rate on some maturities and not others.

depend on past history, as before). In contrast, blue bonds are auctioned. From the fiscal perspective, red bonds and blue bonds are identical: both constitute a promise to deliver a dollar to the holder at the beginning of the subsequent period. We assume that taxes are set according to a fiscal policy rule that satisfies Assumptions 3 and 4, where B_t refers to the total amount of bonds (red and blue). In addition, we need to specify a rule that describes the supply of blue bonds at auction, as a function of past history. Letting B_t^B be the amount of blue bonds being auctioned in period t and maturing in period $t+1$, we assume that this rule satisfies the following assumption[32]:

Assumption 6.

$$0 \le B_t^B < P_{t-1}\overline{G} + B_{t-1} + M_{t-1} - \frac{\beta P_{t-1}\overline{u}_y}{\underline{u}_y(\overline{G})} - T_t, \tag{40}$$

where $\overline{u}_y$ is defined in Eq. (26), with $\overline{R} = \infty$ if no upper limit is imposed on the interest rate.[33]

It is straightforward to prove that Assumption 6 is sufficient for the existence of an interior equilibrium, in which private agents hold a strictly positive amount of red bonds. The allocation and price system in this equilibrium coincide with the one computed in Section 3. In this equilibrium, blue bonds, red bonds, and privately-issued bonds are perfect substitutes from the household perspective, and trade at the same interest rate. That the central bank targets a narrower segment of the bond market is thus immaterial for its ability to control inflation and real activity.

In the event of a run, the presence of blue bonds makes a difference. Households again perceive blue bonds, red bonds, and privately-issued bonds as perfect substitutes. But if a run occurs in period t, the interest rate R_t sanctioned by the central bank for red bonds is lower than the private-sector rate $\hat{R}_t$, and consequently households do not buy any red bonds. At the same time, if a positive amount of blue bonds is offered at auction, households will bid for them, at the interest rate $\hat{R}_t$. The evolution of money supply in period t will thus be governed by the following equation[34]:

$$M_t = P_{t-1}\overline{G} + M_{t-1} + B_{t-1} - T_t - \frac{B_t^B}{1+\hat{R}_t}. \tag{41}$$

Ceteris paribus, the sale of blue bonds reduces the monetization of maturing government debt, alleviating the consequences of the run. We can illustrate this point using our numerical example once again. Let all the parameter values, the initial conditions, and the rules for T_t and R_t be those of Section 4, but assume that, in each period, blue bonds are supplied according to the following rule: $B_t^B = 0.4(B_{t-1} + M_{t-1})$, so that, in steady state, blue bonds represent roughly 2/3 of government debt. In this case, if a run occurs in period s, government debt B_s does not drop from 1.51 to 0, but to 0.99. Because of this, the increase in money supply is more contained: money supply rises from.96 to 2.18 (rather than 2.46). This in turn alleviates the effect on consumption, that falls from 0.96 to 0.64 (rather than 0.6), on the nominal interest rate (rising to 2.56 rather than 3.28), and prices (rising on impact to 3.52 rather than 4.08).[35]

The blue bond–red bond model suggests that a central bank would be well advised to peg the interest rate in a narrow segment of the market, rather than across the entire spectrum of available bonds. When no run occurs, the two strategies implement the same set of equilibria. But, when the risk of runs is present, the consequences of a broad peg are more acute than those of a policy that sets the price in a narrower market. This conclusion provides a rationale for the widespread practice among central banks to set interest rate targets only for very short-term rates, rather than trying to impose an entire yield curve on the market. Even in recent times, when several central banks have tried to affect the yield curve by policies of "quantitative easing," it is noteworthy that they chose to do so by setting an *interest rate target* for the short end, and a *quantity target* for their purchases of longer-term securities.[36] (It is also noteworthy that the Fed's attempt to peg the entire yield curve in the 1940's ultimately led the Fed to be the sole purchaser of short-term Treasury debt.)

6. Conclusion

In this paper, we have shown that considering *bounds* on open market operations may be crucial in determining the size of the set of monetary equilibria under interest rate rules. Policies which have unique equilibria in environments with no bounds may instead have many new equilibria when bounds are introduced. The nature of these new equilibria depends on the specific bounds that the central bank sets: inflation will be much higher if the central bank stands ready to monetize the entire government debt at a given rate than in the more plausible scenario where the interest-rate peg is abandoned at a tighter bound. While we do not offer in this paper a theory of when a run is more or less likely, it is plausible that private expectations will be less stable (and thus more prone to runs) the higher the inflationary consequences of a run. For this reason, we view the recent large excess reserves held by commercial banks as a potential danger. Put simply, it is one thing

[32] Assumption 4 ensures that the interval for B_t^B is nonempty after all histories.

[33] $\overline{u}_y$ will be finite under either Assumption 1 or Assumption 2.

[34] This equation is derived from (1), by assuming that in the event of a run red bonds are 0 and thus $B_t = B_t^B$.

[35] At first blush, the effect of blue bonds on the allocation and prices may seem surprisingly small, considering that they represent 2/3 of government debt in steady state. This happens because, according to the rule that we specified, the government auctions a *fixed nominal future repayment*. Given the very high nominal interest rates that prevail in a run, the real revenues raised by the auction in the event of a run are comparatively modest.

[36] In our simple model, of course, quantitative easing would have no effect on the equilibrium allocation and prices. But our results would apply equally well to richer environments where a preferred habitat is present.

for the central bank to stop buying the debt of the fiscal authority to stop a run. It is altogether a different thing for a central bank to require a sudden large increase in required reserves which would require legal intervention and could be viewed as a refusal to honor its own debts. Goodfriend (2002) argues that a floor system with excess reserves offers a desirable second instrument of monetary policy; this is particularly the case when the policy rate is close to zero and there is little room to use the conventional instrument. Mitigating the risks that we highlighted suggests not to expand excess reserves beyond what is strictly needed to achieve the liquidity benefits that Goodfriend discusses, and to prepare a clear strategy for a quick exit should the need arise.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jmoneco.2015.03.002.

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