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Abstract

In this paper, we provide a simple framework to show the existence of stationary bubbles on dividend-yielding financial assets. These bubbles are compatible with a positive stationary fundamental value, rather than requiring its collapse in the long run. This result is obtained in an exchange overlapping generations economy with vintage financial assets that depreciate over time. New assets are introduced in each period, ensuring a constant aggregate supply of financial assets. Depreciation introduces a gap between the return of bubbles and the rate at which the dividends are discounted. Because the return of bubble can be lower or equal to the growth rate, we can have stationary equilibria with both a positive bubble and a positive fundamental value. Finally, our framework also allows us to discuss the role of the substitutability between financial assets on the level of bubbles and fundamental values.

JEL Classification: E21, E44, G12.
Keywords: Rational bubbles, financial assets, fundamental value.

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1 Introduction

The 2008 financial crisis has generated renewed interest in the study of rational asset price bubbles and their macroeconomic effects. This renewed focus has led to the development of dynamic general equilibrium models aimed at better aligning theoretical models with observed data. Notable contributions include Kocherlakota (2009), Farhi and Tirole (2012), Martin and Ventura (2012), Hirano and Yanagawa (2017). A significant characteristic of this literature is the introduction of bubbles on an asset that does not pay dividends and, therefore, has no fundamental value, such as fiat money. However, bubbles at the origin of the 2008 financial crisis concerned dividend-yielding assets like housing, land and stock. Therefore, there is a need for a theory explaining the behavior of rational bubbles on assets with a fundamental value. Our paper aims to address this gap by developing a model in which a stationary bubble exists on assets with a positive fundamental value.

In line with Clain-Chamosset-Yvrard *et al.* (2023), we develop a three-period overlapping generations (OLG) exchange economy. In each period, new assets are introduced and traded in the market alongside assets from previous periods, leading us to consider a model with vintage assets. We also assume that assets depreciated overtime and yield dividends in terms of utility services, giving them a positive fundamental value. These assets are very close to those considered by Galí (2014), with the notable difference that in Galí (2014), assets are intrinsically worthless. The introduction of dividends allows us to explore the possible existence of price bubbles linked to dividend-paying assets. We also introduce a perfect credit market in which agents trade bonds for saving or borrowing. In particular, young households borrow through bonds and buy a portfolio of vintage assets, because they generate utility services when adult, while adult households save through bond for consumption in old age. Finally, we assume that the utility services from assets make assets of different vintages imperfect substitutes. This introduces heterogeneity between assets of different vintages, an interesting property if we want to interpret theses assets as houses, land or company stocks.

Incorporating vintage assets into three-period OLG model, our paper shows that a stationary price bubble can exist when dividends have a positive stationary value. This implies that the asset price at the steady state contains both a positive fundamental value and a bubble component. This result requires that the return factor on the fundamental component of the vintage asset portfolio is strictly greater than one and the return factor on the bond is lower than one. Households in our model buy portfolios of assets with a bubble component, provided the return of the bubble equals the bond return. Since the return of the bubble equals the growth factor of the bubble, this return should not surpass the economy's growth factor of one to ensure bubble sustainability. Additionally, the fundamental value converges to a finite amount if its return factor exceeds one. Such conditions are feasible in our model due to two key assumptions: the depreciation of assets and the introduction of new assets in each period. A positive depreciation rate makes it possible to disconnect the return on the fundamental component from the bubble's growth, ensuring a return on the fundamental component that is strictly higher than the bubble's growth. Meanwhile, the introduction of new assets is essential to offset the decrease in asset supply due to depreciation, thus maintaining a constant asset supply, which is crucial for a stationary model.

The model exhibits two steady states where asset prices comprise both a fundamental and a bubble component. In both steady states, the bond return factor is smaller than one, leading to a reduced size of the bubble associated with each vintage asset. However, the introduction of new bubbles, linked to new assets, compensates for this reduction, ensuring a positive stationary bubble component in the portfolio value. In the absence of new bubbles, the bond return factor should equal one to maintain a stationary aggregate bubble. The introduction of new bubbles, allocated as endowments to younger households, injects liquidity into the market. As a result, younger households decrease their loan demands, and adult households increase their deposits, leading to a reduction in the bond return. This result aligns with Martin and Ventura (2012) and Galí (2014), with the notable difference that in our model, unlike in their studies, the assets have a fundamental value.

We also show that the fundamental value of the asset is lower at the steady state with the highest value of the bubble component. Furthermore, vintage assets exhibit a higher fundamental value in both steady states when there is a lower degree of substitutability among them. Indeed, the supply of a vintage asset declines with its vintage period and the households' demand for this asset stays significant when assets are weak substitutes. This implies that the fundamental value of assets increases.

The effect of substitutability on the bubble component is more ambiguous. The explanation relies on the bond market in which the interest factor is determined. An increase in the substitutability of assets negatively impacts both the demand for loans and the supply of deposits, leading to an undetermined effect on the equilibrium interest factor. Since the interest factor determines the value of the bubble, it explains why higher substitutability between assets increases the value of the bubble in one steady state and decreases it in the other.

Our paper contributes to the literature on rational bubbles in dividend-paying assets. Building upon the seminal paper of Wilson (1981), as well as Tirole (1985) and Weil (1990), recent studies have demonstrated the existence of bubbles in assets paying dividends, under the condition that dividends become asymptotically negligible compared to the economy. Michau *et al.* (2023), considering wealth in the utility function and an infinitely-lived asset paying dividends in a Ramsey model, show that an asymptotic bubbly steady state equilibrium is possible if the flow of dividends diminishes in the long run. Comparable results are also observed in different models developed by Bosi *et al.* (2017) and Bosi *et al.* (2018). Considering an unbalanced growth model, Hirano *et al.* (2022) and Hirano and Toda (2023a, 2023b) show the existence of bubbles, with the caveat that these bubbles are non-stationary, implying that the fundamental value relative to the asset price becomes negligible. In contrast to these studies, our paper introduces a model where a stationary asset price bubble attached to an asset with a positive and finite fundamental value may exist.

Kamihigashi (2008) introduces an infinite-horizon model that incorporates wealth into the utility function. Within this framework, it becomes possible for an asset price bubble to emerge, even in assets with a fundamental value (see Michau *et al.* (2023) for a related result). As the asset price is included in the utility, asset price growth is lower than economic growth, implying that there cannot exist a stationary bubble. This contrasts with our paper, where we demonstrate the existence of a bubble in the steady state.

To examine the welfare effects of a housing bubble, Graczyk and Phan (2019) develop a pure exchange OLG model where houses can generate utility up to a certain satiation level. They show that a stationary bubble emerges only when the satiation level is reached, at which point houses become intrinsically worthless, generating no additional utility and thus having no fundamental value. In contrast, our study reveals that a stationary bubble can exist when assets continue to provide utility, thereby retaining a fundamental value.

Lastly, Miao and Wang (2018) investigate the emergence of bubbles in firm stock prices in an infinite-horizon model with credit market imperfections. The existence of such a bubble requires the presence of borrowing constraints, which allows to disconnect the growth rate of stock price bubble from the dividend discount rate. The market value of a firm is determined by its wealth, which includes both capital and a bubble component. As stakeholders, households effectively hold this wealth and, thus, invest in both capital and a bubble, akin to fiat money or liquidity. The bubble in their model is defined as the excess of the stock market value over the capital value, which differs with our definition and those in the contributions we mention above, where a bubble is defined as the difference between the equilibrium asset price and its fundamental value.

To conclude, our paper contributes to the literature by showing that the steady-state price of an asset can contain a positive bubble component even if it also has a positive fundamental value in the long run. Therefore, our paper provides a simple model that allows us to study bubbles linked to dividend-paying assets and that could be extended and used in several directions, for example, to study how public policies affect bubbles.

The rest of the paper is organized as follows. Section 2 introduces the model. In Section 3, we present the asset market and define the intertemporal equilibrium. Steady states with a bubble are studied in Section 4. A last section provides concluding remarks, whereas some technical details are relegated to an Appendix.

2 A model with vintage financial assets

We study an overlapping generations (OLG) exchange economy populated by a constant number of individuals that live for three periods: young, adult and old. Each generation is formed by a constant amount of identical individuals that we normalize to one. Time is discrete ($t = 0, 1, ..., +\infty$).

There are two types of assets in the economy: one-period bonds and financial assets. We assume that financial assets provide utility to households. It is a way to introduce a positive fundamental value to these assets. These assets can be seen as houses, land or stock companies. A new asset is introduced in each period and assets undergo partial depreciation at the rate $\delta \in (0, 1)$. Finally, in each period there is an infinite number of financial assets introduced in previous periods, possibly before period $t = 0$. These financial assets are very close to those considered by Galí (2014) and, more recently, by Bonchi (2023), Dong *et al.* (2020) and Dong and Xu (2022), with the remarkable difference that in these papers financial assets have no fundamental value. Therefore, the novelty of our model is the introduction of a fundamental value on these assets.

Each household born in t obtains utility from consumption at each period of **her** lifetime, and from holding financial assets in period $t + 1$. Preferences are represented by an additively separable life-cycle utility function:

$$\alpha lnc_{1,t} + \beta \left[(1 - \mu) lnc_{2,t+1} + \mu ln \left(\sum_{k=0}^{+\infty} h^{\rho}_{t+1|t-k} \right)^{\frac{1}{\rho}} \right] + \gamma lnc_{3,t+2} \tag{1}$$

where $\alpha, \beta, \gamma > 0$, $\alpha + \beta + \gamma = 1$, $0 \leq \mu < 1$ and $\rho \leqslant 1$. $c_{i,t}$ and $h_{t+1|t-k}$ denote, respectively, consumption at period t when young ($i = 1$), adult ($i = 2$) and old ($i = 3$), and the quantity at period $t+1$ of vintage financial asset introduced in $t-k$. The parameter ρ determines the susbstitutability between financial assets of different vintages. When $\rho < 1$, financial are assets are imperfect substitutes, the substitutability increases with ρ and financial assets are perfect substitutes when $\rho = 1$.

In her first period of life, the household is young. She is endowed with $\omega > 0$ units of a consumption good and $\delta \in (0, 1)$ units of a new financial asset. For the sake of simplicity, we assume that new endowments of financial assets coincide with their depreciation. In this way, the total stock of financial assets remains constant. She uses the endowments to consume $c_{1,t}$ units of a consumption good, have deposits/loans $a_{1,t}$ in bonds, and buy $h_{t+1|t-k}$ units of the vintage financial asset introduced in period $t - k$ at price $p_{t|t-k}$. Note that $p_{t|t-k} \geq 0$ is the real price in period t of a financial asset introduced in period $t - k$. In her second period of life, the household is an adult. She receives no endowments, but the returns on deposits/loans $R_{t+1}a_{1,t}$ and sells financial assets $h_{t+1|t-k}$ at price $p_{t+1|t-k}$. As the quantity of financial assets depreciates at rate $\delta \in (0, 1)$, she obtains $(1 - \delta)p_{t+1|t-k}h_{t+1|t-k}$ for each asset. Furthermore, she consumes $c_{2,t+1}$ units of the consumption good and has deposits/loans $a_{2,t+1}$. In her third period, she is old. She receives no endowments, but the returns on her savings $R_{t+2}a_{2,t+1}$, and consumes $c_{3,t+2}$. Note that when $a_{i,t} < 0$, the households contract loans, and when $a_{i,t} > 0$, they make deposits. We consider agents living three periods to precisely have this heterogeneity of behaviours on the bond market and have savers that coexist with borrowers at the same time.

The budget constraints in the three periods of life are:

$$c_{1,t} + a_{1,t} + \sum_{k=0}^{+\infty} p_{t|t-k} h_{t+1|t-k} = \omega + p_{t|t}\delta \tag{2}$$

$$c_{2,t+1} + a_{2,t+1} = R_{t+1} a_{1,t} + (1-\delta) \sum_{k=0}^{+\infty} p_{t+1|t-k} h_{t+1|t-k} \tag{3}$$

$$c_{3,t+2} = R_{t+2} a_{2,t+1} \tag{4}$$

A household born at period t chooses consumption $c_{1,t}, c_{2,t+1}$ and $c_{3,t+2}$, deposits/loans $a_{1,t}$ and $a_{2,t+1}$, and $\left\{h_{t+1|t-k}\right\}_{k=0}^{\infty}$ units of assets introduced in past periods to maximize the utility function (1) subject to the budget constraints (2)-(4). The optimal behaviour of this household is summarized by the following equations:

$$\frac{\alpha}{\beta(1-\mu)} \frac{c_{2,t+1}}{c_{1,t}} = R_{t+1} \; , \; \frac{\beta(1-\mu)}{\gamma} \frac{c_{3,t+2}}{c_{2,t+1}} = R_{t+2} \tag{5}$$

$$p_{t|t-k} R_{t+1} = (1-\delta) \left(p_{t+1|t-k} + div_{t+1|t-k}\right) \quad \forall k > 0 \tag{6}$$

$$\text{with} \qquad div_{t+1|t-k} \equiv \frac{\mu}{1-\mu} \frac{c_{2,t+1}}{1-\delta} \frac{h_{t+1|t-k}^{\rho-1}}{\sum_{k=0}^{+\infty} h_{t+1|t-k}^{\rho}} \tag{7}$$

Eq. (5) depict the standard intertemporal trade-off between consumption at different periods of time. Eq. (6) is the non-arbitrage condition between financial assets $h_{t+1|t-k}$ and bonds $a_{1,t}$, which defines the asset price $p_{t|t-k}$. Finally, we note that the dividend $div_{t+1|t-k}$ depends on the vintage period of the asset when $\rho < 1$. Therefore, assets from a different vintage have different dividends when they are imperfect substitutes. More precisely, the dividend decreases with the quantity of the asset when $\rho < 1$. Since assets depreciate, the supply of an asset of an older vintage is smaller and, hence, the dividends will be larger when $\rho < 1$.

Using the budget constraints (2)-(4), we finally obtain the following optimal solutions:

$$c_{1,t} = \alpha(\omega + \delta p_{t|t}) \tag{8}$$

$$c_{2,t+1} = R_{t+1}\beta(1-\mu)(\omega + \delta p_{t|t}) \tag{9}$$

$$c_{3,t+2} = R_{t+2}R_{t+1}\gamma(\omega + \delta p_{t|t}) \tag{10}$$

$$a_{1,t} + \sum_{k=0}^{+\infty} p_{t|t-k} h_{t+1|t-k} = (\beta+\gamma)(\omega + \delta p_{t|t}) \tag{11}$$

$$a_{2,t+1} = R_{t+1}\gamma(\omega + \delta p_{t|t}) \tag{12}$$

$$\sum_{k=0}^{+\infty} p_{t|t-k} h_{t+1|t-k} = \frac{1-\delta}{R_{t+1}} \left(\sum_{k=0}^{+\infty} p_{t+1|t-k} h_{t+1|t-k} + div_{t+1} \right) \tag{13}$$

$$\text{with} \quad div_{t+1} = R_{t+1} \frac{\beta\mu}{1-\delta} (\omega + \delta p_{t|t}) \tag{14}$$

where Eq. (13) defines the value of asset portfolio and it is obtained by aggregating Eq. (6) over all financial assets.

3 Asset markets and equilibrium

We distinguish between a market for one-period riskless bond and markets for each financial assets. The market clearing condition for bonds is $a_{1,t} + a_{2,t} = 0$. It implies that deposits are used for loans, which explains that loans and deposits provide the same return R_{t+1}. Indeed, from (12) we deduce that $a_{2,t} > 0$, which implies that $a_{1,t} < 0$, i.e., bonds are used by adults to save and by young individuals to borrow.

Let us focus now on financial assets. On the one hand, the supply of each financial asset depreciates at the rate δ in each period. On the other hand, an amount δ of new financial asset is introduced in each period. This means that $h_{t+1|t} = \delta$ and $h_{t+1|t-k} = \delta(1-\delta)^k$. Therefore, the total supply of financial assets remains constant and equal to one, which implies that:

$$\sum_{k=0}^{+\infty} h_{t+1|t-k} = 1 \tag{15}$$

At this point, we introduce two important remarks. First, this model with vintage financial assets assumes that some financial assets are introduced before period $t = 0$ when $k > t$ and, at period 0, there exists an infinite number of assets whose seniority is measured by $\delta(1-\delta)^k$, with $k \geqslant 1$. This is a usual assumption in models with vintage capital, as for instance in Boucekkine *et al.* (2005), which is introduced to ensure that the total supply of assets remains constant.

Second, we note that, on the one hand, if $\delta = 0$, no financial assets are introduced in the economy, which means that there is no supply of assets. On the other hand, if $\delta = 1$, financial assets last for one period. Therefore, they only correspond to a flow of consumption goods in the young age. These two cases are not relevant for our analysis. Therefore, we assume that $\delta \in (0, 1)$.

Before analysing the equilibrium of this economy, we determine the equilibrium asset price and discuss the notion of asset price bubble. From Eq.(6), the asset price $p_{t|t-k}$ can be written as:

$$\begin{aligned} p_{t|t-k} &= \frac{1-\delta}{R_{t+1}} \left(p_{t+1|t-k} + div_{t+1|t-k} \right) \\ &= \underbrace{\sum_{i=1}^{\infty} \frac{(1-\delta)^i \, div_{t+i|t-k}}{\Pi_{s=1}^{i} R_{t+s}}}_{f_{t|t-k}} + \underbrace{\lim_{j\to\infty} \frac{(1-\delta)^j \, p_{t+j|t-k}}{\Pi_{s=1}^{j} R_{t+s}}}_{b_{t|t-k}} \end{aligned} \tag{16}$$

where $f_{t|t-k}$ is the fundamental value of the asset introduced in period $t - k$

and $b_{t|t-k}$ is the bubble component of the price, satisfying:

$$
\begin{aligned}
f_{t|t-k} &= \frac{1-\delta}{R_{t+1}}\left(f_{t+1|t-k} + div_{t+1|t-k}\right) && (17)\\
b_{t|t-k} &= \frac{1-\delta}{R_{t+1}} b_{t+1|t-k} \quad \forall k \geq 0 && (18)
\end{aligned}
$$

Let $p_t = \sum_{k=0}^{+\infty} p_{t|t-k} h_{t+1|t-k} = \delta \sum_{k=0}^{+\infty} (1-\delta)^k p_{t|t-k}$, which represents the value of the asset portfolio at equilibrium. Referring to Eq. (13), we can deduce that the asset portfolio value evolves as follows[1]:

$$
\begin{aligned}
p_t &= \frac{p_{t+1} - \delta p_{t+1|t+1} + div_{t+1}}{R_{t+1}} && (19)\\
\text{with} \quad div_{t+1} &= \frac{\mu}{1-\mu} \frac{c_{2,t+1}}{1-\delta} && (20)
\end{aligned}
$$

Moreover, using Eq. (16), we also obtain that the asset porfolio value equals:

$$
p_t = \sum_{k=0}^{+\infty} p_{t|t-k} h_{t+1|t-k} = \sum_{k=0}^{+\infty} f_{t|t-k} h_{t+1|t-k} + \sum_{k=0}^{+\infty} b_{t|t-k} \delta \left(1-\delta\right)^k . \qquad (21)
$$

Therefore, the asset portfolio value can be written as:

$$
p_t = f_t + b_t + u_t, \qquad (22)
$$

where $f_t \equiv \sum_{k=0}^{+\infty} f_{t|t-k} h_{t+1|t-k}$ is the fundamental component of asset portfolio value, $b_t \equiv \sum_{k=1}^{+\infty} b_{t|t-k} \delta \left(1-\delta\right)^k$ is the bubble component of the asset portfolio value without considering the new asset and $u_t \equiv \delta b_{t|t}$ is the bubble component of the new asset. We can also deduce that the value of a new asset distributed as an endowment to a young household born at period t is:

$$
\delta p_{t|t} = \delta f_{t|t} + u_t \qquad (23)
$$

where $f_t \neq f_{t|t}$. Although the fundamental value of asset portfolio f_t and that of a new asset $f_{t|t}$ are different, we will show that they are link by a simple relationship. Using (7), (14) and (17), we obtain that the fundamental value of a new asset introduced at period t is given by:

$$
\begin{aligned}
f_{t|t} &= \frac{1-\delta}{R_{t+1}}\left(f_{t+1|t} + div_{t+1|t}\right) && (24)\\
\text{with} \quad div_{t+1|t} &= div_{t+1} \frac{h_{t+1|t}^{\rho-1}}{\sum_{k=0}^{+\infty} h_{t+1|t-k}^{\rho}} = \Omega div_{t+1} && (25)\\
\text{and} \quad \Omega &\equiv \frac{1}{\delta \sum_{k=0}^{+\infty} [(1-\delta)^{\rho}]^k} && (26)
\end{aligned}
$$

Ω determines the relationship between the parameter ρ and the dividends generated by new assets. This relationship is analyzed in the following lemma:

[1]See also Appendix A.

Lemma 1

1. *When* $\rho \leqslant 0$, Ω *tends to 0*

2. *When* $\rho \in (0,1]$, $\Omega = \frac{1-(1-\delta)^{\rho}}{\delta} \in (0,1]$. Ω *is increasing in* ρ, *with* $\lim_{\rho \to 0} \Omega = 0$ *and* $\Omega = 1$ *when* $\rho = 1$.

Proof. See Appendix B. ■

This lemma implies that dividends of new assets are zero when $\rho \leqslant 0$. In this case, $\sum_{k=0}^{+\infty} h_{t+1|t-k}^{\rho} = \sum_{k=0}^{+\infty} [\delta(1-\delta)^k]^{\rho}$ tends to $+\infty$ and the utility function (1) has not a finite value. To ensure a positive dividend and a finite value of the utility function, we restrict our attention to configurations where $\Omega \in (0,1]$, i.e. we assume:

Assumption 1 $\rho \in (0,1]$, *which implies that* $\Omega = [1-(1-\delta)^{\rho}]/\delta$.

Lemma 1 shows that Ω increases with ρ when Assumption 1 is satisfied. Therefore, Ω increases when financial assets become better substitutes. We next show that Ω also sets the relationship between the fundamental value of new assets, $f_{t|t}$, and that of asset portfolio, f_t.

Lemma 2 *The relationship between* $f_{t|t}$ *and* f_t *is given by:*

$$f_t = \sum_{k=0}^{+\infty} f_{t|t} \delta (1-\delta)^{\rho k} = f_{t|t}/\Omega \tag{27}$$

Proof. See Appendix C. ■

Eq. (27) is of course equivalent to $f_{t|t} = \Omega f_t$, with $\Omega \leqslant 1$. This equation and Lemma 1 imply that the fundamental value of a new asset relative to the fundamental value of asset portfolio declines as assets become worse substitutes. Recall that the supply of an asset decreases with the vintage period. As the substitutability among assets declines, the households demand for each older assets remains significant, which implies that older vintages become more valuable. This explains why the fundamental value of new assets relative to existing assets decreases when assets become less substitutable.

Finally, in Appendix A, we use (19), (22), (23) and Lemma 1 to deduce that the evolution of the bubble and fundamental components of the asset portfolio value satisfy:

$$b_t + u_t = \frac{b_{t+1}}{R_{t+1}} \tag{28}$$

$$f_t = \frac{1-\delta\Omega}{R_{t+1}} f_{t+1} + \frac{div_{t+1}}{R_{t+1}} \tag{29}$$

Before characterizing the intertemporal equilibrium, we discuss the existence of an asset price bubble with positive dividends. First, for households to hold a portfolio containing a bubble within its value, the bubble must provide the same return as bonds, and thus the value of the bubble grows by a factor of R_{t+1}. This return factor must be lower than or equal to the economy's growth factor, meaning $R_{t+1} \leq 1$. Otherwise, the bubble will grow too rapidly to be sustainable.

Second, Eq. (29) can be rewritten as:

$$f_t = \frac{f_{t+1} + \bar{div}_{t+1}}{\bar{R}_{t+1}} \tag{30}$$

$$with \quad \bar{R}_{t+1} \equiv \frac{R_{t+1}}{1-\delta\Omega}, \quad \bar{div}_{t+1} \equiv \frac{div_{t+1}}{1-\delta\Omega} \tag{31}$$

where $\bar{div}_{t+1}$ measures the aggregate dividend received for a unit invested in portfolio in t and $\bar{R}_{t+1}$ represents the fundamental return factor of asset portfolio. Given that aggregate dividends are always positive, the fundamental value of asset portfolio converges to a finite value if the fundamental return factor is greater than one, namely the growth factor of dividends. Under Assumption 1, such a return factor implies that the fundamental value of an asset introduced in $t-k$, defined by Eq. (17), is also finite.

Therefore, in our model, a non-explosive bubble can coexist with a finite fundamental value if the return factor of bonds satisfies the following inequality:

$$1 - \delta\Omega < R_{t+1} \leq 1 \text{ or equivalently } R_{t+1} \leq 1 < \bar{R}_{t+1} \tag{32}$$

Such a condition is possible in our framework because of two assumptions: the depreciation of assets and the introduction of new assets in each period. A positive depreciation rate $\delta \in (0,1)$ allows to disconnect the return of the fundamental value from the growth of the bubble, and more precisely to get a fundamental return strictly higher than the bubble growth. The introduction of new assets is necessary to counterbalance the reduction in asset supply caused by depreciation, thereby maintaining a constant asset supply necessary for a stationary model.

Lastly, we note that if such a condition is satisfied, then the bubble size attached to vintage assets introduced in period $t-k$ is also non-explosive and may decrease over time. Indeed, using Eq. (18), we have:

$$\frac{b_{t+1|t-k}h_{t+2|t-k}}{b_{t|t-k}h_{t+1|t-k}} = \frac{b_{t+1|t-k}}{b_{t|t-k}}\frac{h_{t+2|t-k}}{h_{t+1|t-k}} = \frac{R_{t+1}}{1-\delta}(1-\delta) = R_{t+1} \tag{33}$$

The increase in prices $b_{t|t-k}$ does not offset the decrease in the asset stock, since it implies a decline in the bubble size of vintage assets if $R_{t+1} < 1$. Nevertheless, the introduction of new bubbles attached to new assets prevents the bubble component of the asset portfolio value from collapsing.

We next characterize the equilibrium. First, we use (11), (12), (22), (23) and Lemma 1 to obtain:

$$\begin{aligned} a_{1,t} &= (\beta+\gamma)(\omega + \delta\Omega f_t + u_t) - f_t - b_t - u_t \\ a_{2t} &= R_t\gamma(\omega + \delta\Omega f_{t-1} + u_{t-1}) \end{aligned}$$

Using these equations and the market clearing on the credit market, $a_{1,t}+a_{2,t} = 0$, we deduce that

$$R_{t+1} = \frac{f_{t+1} + b_{t+1} + u_{t+1} - (\beta+\gamma)(\omega + \delta\Omega f_{t+1} + u_{t+1})}{\gamma(\omega + \delta\Omega f_t + u_t)} \tag{34}$$

Second, using (14) and (29), the equilibrium on the asset market can be written as:

$$R_{t+1} = \frac{f_{t+1}(1-\delta\Omega)}{f_t - \beta\mu(\omega + \delta\Omega f_t + u_t)} \tag{35}$$

Using equations (28), (34) and (35), we obtain the following two-dimensional dynamic system:

$$\frac{b_{t+1}}{b_t + u_t} = \frac{f_{t+1} + b_{t+1} + u_{t+1} - (\beta+\gamma)(\omega + \delta\Omega f_{t+1} + u_{t+1})}{\gamma(\omega + \delta\Omega f_t + u_t)} \tag{36}$$

$$\frac{b_{t+1}}{b_t + u_t} = \frac{f_{t+1}(1-\delta\Omega)}{f_t - \beta\mu(\omega + \delta\Omega f_t + u_t)} \tag{37}$$

Definition 1 *Given the path of shocks $\{u_t\}_{t=0}^{\infty}$, an equilibrium with bubbles is a path of $\{b_t, f_t\}_{t=0}^{\infty}$ that satisfies (36) and (37), with $b_t > 0$ for all $t \geqslant 0$.*

Note that both variables depend on expectations on the next period and are therefore not predetermined.

In the next section, we show that bubbles attached to an asset paying dividends may exist at a steady state.

4 Bubbly steady states

Let the bubble shock be stationary, i.e. $u_t = u_{t+1} = u > 0$. A steady state is a solution $b_t = b_{t+1} = b$ and $f_t = f_{t+1} = f$ to equations (36)-(37).

Eq. (37) gives the equilibrium condition:

$$f = \frac{b\mu\beta(\omega+u)}{b(1-\mu\beta)\delta\Omega - u(1-\delta\Omega)} \tag{38}$$

Let us introduce the following critical value:

$$\underline{b} \equiv \frac{u(1-\delta\Omega)}{(1-\mu\beta)\delta\Omega} > 0 \tag{39}$$

To ensure $f > 0$, we assume that $b > \underline{b}$. Using (38), we also have:

$$\omega + \delta\Omega f + u = \frac{(\omega+u)[b\delta\Omega - u(1-\delta\Omega)]}{(1-\mu\beta)\delta\Omega(b-\underline{b})} \tag{40}$$

$$f + b + u = \frac{b\mu\beta(\omega+u) + (b+u)(1-\mu\beta)\delta\Omega(b-\underline{b})}{(1-\mu\beta)\delta\Omega(b-\underline{b})} \tag{41}$$

Then, the equilibrium condition obtained using (36):

$$(\omega + \delta\Omega f + u)[(\beta + 2\gamma)b + (\beta + \gamma)u] = (f + b + u)(b + u)$$

is equivalent to:

$$F(b) = G(b) \tag{42}$$

with

$$\begin{aligned} F(b) &\equiv b(\omega + u)[\gamma + \mu\beta(\beta + \gamma)][b(\Delta_1 - \delta\Omega) + u(\Delta_0 - \delta\Omega)] && (43) \\ G(b) &\equiv \delta\Omega(1 - \beta\mu)(b + u)(b - \underline{b})(\overline{b} - b) && (44) \end{aligned}$$

and

$$\Delta_1 \equiv \frac{\beta\mu}{\gamma + \beta\mu(\beta + \gamma)},\ \Delta_0 \equiv \frac{\gamma + \beta\mu}{\gamma + \beta\mu(\beta + \gamma)} > 1 \textit{ and } \overline{b} \equiv (\beta + \gamma)\omega - \alpha u,$$

We assume that $\overline{b} > \underline{b}$, which holds when the following assumption is satisfied:

Assumption 2 $\omega > \frac{u}{\beta+\gamma}\left[\alpha + \frac{1-\delta\Omega}{\delta\Omega(1-\beta\mu)}\right]$.

Using equations (42)-(44), we obtain the bubbly steady states. The results of this analysis are summarized in the following proposition.

Proposition 1 *Under Assumptions 1 and 2, and $u > 0$, there exists two values of Ω, Ω^0 and Ω^1, such that:*

1. *For $\Omega > \Omega^1$, there exist two steady states b_1 and b_2, such that $\underline{b} < b_1 < \overline{b} < b_2$.*
2. *For $0 < \Omega^0 < \Omega < \Omega^1$, there exist two steady states, b_1 and b_2, such that $\underline{b} < b_1 < b_2 < \overline{b}$ if u is small enough.*
3. *For $\Omega < \Omega^0$, there is no steady state with bubble.*

Moreover, if $\delta\Omega$ close to Δ_1, u and μ small, b_1 is a source and b_2 is a saddle.

Proof. See Appendix D. ■

This proposition shows that two bubbly steady states may exist. In such a case, a stationary asset price bubble exists on an asset with a fundamental value, even if the dividend keeps a constant and positive value. Indeed, Condition (32) is satisfied at a steady state, namely

$$R < 1 < \frac{R}{1 - \delta\Omega} \tag{45}$$

By inspection of Eqs. (29) and (38), we observe that the aggregate fundamental value may jump on a finite value f. This is a necessary condition for an asset price bubble to be sustained as otherwise young households could not buy the asset.

A stationary positive aggregate bubble necessitates an interest factor R smaller than 1 when new bubbles emerge in the economy in each period. This is also a necessary condition for a bubble to be sustained, otherwise the aggregate bubble would be explosive. Upon examining Eq. (33), it becomes evident that such an interest factor results in a reduced size of the bubble associated with each vintage asset. The introduction of new bubbles linked to new assets offsets this reduction, ensuring a positive stationary bubble component in the asset portfolio value. This condition echoes findings in Martin and Ventura (2012) and Galí (2014), with a key distinction being that those authors consider assets with no fundamental value. The underlying rationale behind this condition can be found in the bond market. In the absence of new bubbles, the bond return factor should equal one to maintain a stationary aggregate bubble. The emergence of new bubbles, allocated as endowments to younger households, injects liquidities into the market. Consequently, younger households reduce their loan demands, while adult households increase their deposits. This shift leads to a decrease in bond returns.

As explained in Section 3, two assumptions allow the existence of a stationary bubble attached to assets with constant and positive dividends. First, a positive depreciation rate $\delta \in (0,1)$ allows to get a return for the fundamental value strictly higher than the bubble growth, ensuring the coexistence of a stationary asset price bubble and a finite and positive fundamental value. Second, the introduction of new assets is necessary to counterbalance the reduction in asset supply caused by depreciation, thereby maintaining a constant asset supply, necessary for a stationary model.

Both the fundamental value f_t and the bubble on asset portfolio value b_t depend on expectations on the next period and are therefore not predetermined. Consequently, the stability results in Proposition 1 imply that the steady state b_1 is locally determinate, while b_2 is a locally indeterminate steady state. This means that at least in a neighborhood of this last steady state, expectation-driven fluctuations could occur. Our model is therefore able to explain the volatility of both the fundamental and bubble components of asset prices.

Proposition 1 only focuses on stationary equilibria with $u > 0$. The next corollary analyses the existence of stationary equilibria when $u = 0$.

Corollary 1 *Under Assumption 1, there exists two steady states when $u = 0$, a bubbleless one ($b = 0$) and a bubbly one $b = \tilde{b} > 0$ if $\delta\Omega > \beta\mu/(\beta + 2\gamma)$, with:*

$$\tilde{b} = \frac{\omega\left[\delta\Omega(\beta + 2\gamma) - \beta\mu\right]}{(1 - \mu\beta)\delta\Omega}$$

Moreover, if $\delta\Omega$ close to Δ_1 and μ small, $\tilde{b}$ is a saddle.

Proof. See Appendix D. ■

Corollary 1 shows that stationary asset price bubble linked to an asset with a positive fundamental value can exist, even without bubble creation ($u = 0$).

When $u_t = 0 \; \forall t \geq 0$, our analysis is limited to a subset of equilibria where the bubble component of the asset portfolio value evolves according to $b_t = b_{t+1}/R_{t+1}$ (see Eq. (28)). Therefore, any bubble must have existed from the beginning of the economy, and a stationary bubble exists if it grows at the same rate as the economy, i.e. $R = 1$. Such a return implies that the bubble size attached to vintage assets introduced in period $t-k$ is also stationary (see Eq. (33)). In this stationary bubbly equilibrium, the increase in prices $b_{t|t-k}$ exactly offsets the decrease in the asset stock which implies that the bubble size of vintage assets remains constant over time. The fundamental value of the asset portfolio $\tilde{f}$ is given by $\tilde{f} = \frac{\beta\mu w}{(1-\beta\mu)\delta\Omega}$.

As for $u_t = u > 0$, the assumption of a positive depreciation rate $\delta \in (0,1)$ allows Condition (32) to be met in this bubbly steady state, as shown by $R = 1 < \frac{R}{1-\delta\Omega}$. Furthermore, the introduction of new assets in each period at a price of $p_{t|t} = f_{t|t}$ helps maintain a constant asset supply, which is essential for a stationary model.[2]

Proposition 1 also shows that a steady state with bubbles does not exist when assets are weak substitutes (Ω close to 0). This occurs because the fundamental value of assets is too large when Ω is low and households cannot buy assets with a bubble component. In this case, an equilibrium with bubbles cannot be sustained.

We confirm now this intuition by studying the effect of substitutability, measured by Ω, on the bubble and fundamental value of assets at the steady state. We denote by f_1 and f_2 the fundamental value at the steady states where the bubble component is, respectively, b_1 and b_2. Using (38), we observe that, as in Kamihigashi (2008), the fundamental value decreases with the value of the bubble. This means that f_2 is smaller than f_1. In the following proposition, we study how b_i and f_i vary with Ω:

Proposition 2 *Under Assumptions 1 and 2, we have the following:*

1. *b_1 and f_1 decrease with Ω when u is sufficiently small.*
2. *b_2 increases and f_2 decreases with Ω if $\delta\Omega < \Delta_1$ or if $\delta\Omega$ is higher but close to Δ_1 and u sufficiently small.*

Proof. See Appendix E. ■

Proposition 2 shows that the fundamental value of assets is larger when financial assets are worse substitutes (lower Ω). The supply of a financial asset declines with its vintage period and the households' demand of this asset stays significant when assets are weak substitutes. As a consequence, households' demand shifts from consumption goods to financial assets when financial assets become worse substitutes. This implies that the fundamental price of financial assets relative to the price of consumption goods increases.

[2] The absence of bubble creation $u_t = 0$ does not imply there is no asset creation. Recall that $u_t = \delta b_{t|t}$. By $u_t = 0$, we mean that $b_{t|t} = 0$.

Proposition 2 also shows that the effect of substitutability on the bubble component of the price of financial assets is ambiguous, since a larger Ω decreases b_1 and increases b_2. This ambiguous effect is explained by the fact that higher substitutability of financial assets reduces both the demand for loans by young households and the supply of deposits by adult households. The effect on the equilibrium interest factor is therefore ambiguous.

On the one hand, the reduction in loan demand by young households is explained by the fact that the price of new assets relative to existing ones is larger when financial assets are better substitutes. Since new assets are an endowment for young households, it turns out that young households require less borrowing to consume and acquire financial assets, especially older ones, when Ω increases.

On the other hand, the value of new financial assets, $p_{t|t}$, declines when Ω increases. As a consequence, households' income declines, which explains the reduction in consumption expenditure. Adult household deposits decrease when consumption expenditure declines.

Since an increase in the substitutability of financial assets reduces both the demand for loans and the supply of deposits, the effect on the equilibrium interest factor is ambiguous and depends on the steady state. Since the interest factor determines the value of the bubble, the combined effect on the demand for loans and on the supply of deposits explains why higher substitutability between financial assets affects the value of the bubble differently in the two steady states.

5 Concluding remarks

We study the equilibrium of an exchange OLG economy in which individuals living three periods smooth consumption using bonds and financial assets that provide a positive dividend. We show that at a steady state, the price of these assets contains a positive fundamental component and also a positive bubble component. This result is a new and important contribution of the literature on rational bubble. Indeed, it is the first paper which shows the existence of a stationary bubble on assets with fundamental values, whereas previous results consider non stationary equilibria.

Households purchase many different assets that provide positive dividends. Therefore, it is interesting to analyze how the characteristics of the household asset demand affect the existence of financial bubbles. In this direction, this paper makes a second contribution by analyzing how financial assets substitutability affects financial bubbles. Specifically, we show that there is no equilibrium with financial bubbles when assets are weak substitutes. Future research could study how other properties of household demand affect financial bubbles.

Appendix

A Derivation of Eqs. (19), (28) and (29)

Let us start with Eq. (19). We have:

$$\begin{aligned}(1-\delta)\sum_{k=0}^{+\infty} p_{t+1|t-k}h_{t+1|t-k} &= (1-\delta)\sum_{k=0}^{+\infty} p_{t+1|t-k}\delta(1-\delta)^k \\ &= \sum_{k=1}^{+\infty} p_{t+1|t+1-k}\delta(1-\delta)^k \\ &= \delta\sum_{k=0}^{+\infty} p_{t+1|t+1-k}(1-\delta)^k - \delta p_{t+1|t+1}\end{aligned}$$

We focus now on the derivation of Eq. (28). We have defined $b_{t+1} \equiv \sum_{k=1}^{+\infty}\delta(1-\delta)^k b_{t+1|t+1-k}$. Using (16), we get:

$$\begin{aligned}\frac{b_{t+1}}{R_{t+1}} &= \sum_{k=1}^{+\infty}\delta(1-\delta)^k \lim_{j\to+\infty}\frac{(1-\delta)^j p_{t+1+j|t+1-k}}{\prod_{s=1}^{j+1} R_{t+s}} \\ &= \sum_{k=0}^{+\infty}\delta(1-\delta)^k \lim_{j\to+\infty}\frac{(1-\delta)^{j+1} p_{t+1+j|t-k}}{\prod_{s=1}^{j+1} R_{t+s}}\end{aligned} \tag{A.1}$$

This equation can be rewritten as:

$$b_t = \sum_{k=1}^{+\infty}\delta(1-\delta)^k \lim_{j\to+\infty}\frac{(1-\delta)^j p_{t+j|t-k}}{\prod_{s=1}^{j} R_{t+s}}$$

which implies that:

$$b_t + u_t = \sum_{k=0}^{+\infty}\delta(1-\delta)^k \lim_{j\to+\infty}\frac{(1-\delta)^j p_{t+j|t-k}}{\prod_{s=1}^{j} R_{t+s}}$$

A comparison between this last equation and (A.1) proves that $b_{t+1}/R_{t+1} = b_t + u_t$.

B Proof of Lemma 1

When $\rho = 0$, it is obvious that $\sum_{k=0}^{+\infty}[(1-\delta)^\rho]^k$ tends to $+\infty$, which implies that Ω tends to 0.

When $\rho \neq 0$, we have:

$$\sum_{k=0}^{+\infty}[(1-\delta)^\rho]^k = \lim_{i\to+\infty}\frac{1-[(1-\delta)^\rho]^{1+i}}{1-(1-\delta)^\rho}$$

When $\rho < 0$, $(1-\delta)^\rho > 1$, which implies that this sum tends to $+\infty$ and Ω tends to 0.

When $1 \geqslant \rho > 0$, $(1-\delta)^\rho < 1$, and we obtain $\Omega = \frac{[1-(1-\delta)^\rho]}{\delta} > 0$. Moreover, since $(1-\delta)^\rho \geqslant 1-\delta$, we have $\Omega \leqslant 1$. Finally,

$$\frac{d\Omega}{d\rho} = -\frac{[\ln(1-\delta)](1-\delta)^\rho}{\delta} > 0$$

because $\ln(1-\delta) < 0$.

C Proof of Lemma 2

Using (7), we have $\frac{div_{t+i|t}}{div_{t+i|t-k}} = \left(\frac{h_{t+i|t}}{h_{t+i|t-k}}\right)^{\rho-1} = (1-\delta)^{k(1-\rho)}$, and using (16), we obtain that

$$\begin{aligned} f_{t|t} &= \sum_{i=1}^{\infty}\frac{(1-\delta)^{i-1}\,div_{t+i|t}}{\Pi_{s=1}^{i}R_{t+s}} \\ f_{t|t-k} &= \sum_{i=1}^{\infty}\frac{(1-\delta)^{i-1}\,div_{t+i|t-k}}{\Pi_{s=1}^{i}R_{t+s}} \end{aligned}$$

From these equations, we easily deduce that $f_{t|t-k} = (1-\delta)^{k(\rho-1)}f_{t|t}$. Finally, using (21), we obtain Eq. (27).

D Proof of Proposition 1 and Corollary 1

The proof of this proposition has three parts. We first show existence of steady states with bubbles, after we analyze the stability properties of these steady states and finally we prove Corollary 1. We proceed with the first part.

To study the existence of steady states, we use equations (43) and (44). Assumption 2 implies that $G(b) < 0$ for $0 < b < \underline{b}$, $G(b) > 0$ for $\underline{b} < b < \overline{b}$, and $G(b) < 0$ for $b > \overline{b}$. In addition, $G(\underline{b}) = G(\overline{b}) = 0$. We also have $\Delta_1 < \Delta_0$ and $\Delta_1 < 1$ if $\alpha\beta\mu < \gamma$. This means that $\Delta_0 - \delta\Omega > 0$ and we have two configurations, either $0 < \delta\Omega < \Delta_1$, or $\Delta_1 < \delta\Omega < 1$. We next use these relationships to show the existence of two steady states.

Let us consider that $\delta\Omega > \Delta_1$. $F(b)$ is an inversely U-shaped function, with $F(0) = 0$ and $F(+\infty) = -\infty$. Using (43), $F(\underline{b})$ has the same sign than $\widehat{F}(\delta\Omega)$, with:

$$\widehat{F}(\delta\Omega) = 1 - \delta\Omega[\beta(1+\mu)+2\gamma] + (\delta\Omega)^2[\gamma+\mu\beta(\beta+\gamma)] \tag{D.2}$$

We show that $\widehat{F}(0) = 1 > 0$, $\widehat{F}'(0) < 0$, $\widehat{F}(1) = \alpha\,(1-\mu\beta) > 0$ and $\widehat{F}'(1) = -\beta[1+\mu-2\mu(\beta+\gamma)] < 0$. We deduce that $\widehat{F}'(\delta\Omega) < 0$ for all $\delta\Omega \in (0,1)$. We deduce that $\widehat{F}(\delta\Omega) > 0$ and, therefore, $F(\underline{b}) > 0$.

Using (43), $F(\overline{b}) < 0$ is equivalent to:

$$[\omega(\beta+\gamma) - \alpha u][\Delta_1 - \delta\Omega] + u(\Delta_0 - \delta\Omega) < 0$$

This is satisfied for $\Omega > \Omega^1$, with:

$$\Omega^1 \equiv \frac{\omega(\beta+\gamma)\Delta_1 + u(\Delta_0 - \alpha\Delta_1)}{[\omega(\beta+\gamma) + (1-\alpha)u]\delta} (> \frac{\Delta_1}{\delta})$$

Since $G(+\infty) < F(+\infty)$, for $\Omega > \Omega^1$, there are two steady states b_1 and b_2 such that $b_1 \in (\underline{b}, \overline{b})$ and $b_2 \in (\overline{b}, +\infty)$.

In the configuration where $\Omega < \Omega^1$, we either have $F(b)$ which is inversely U-shaped with $F(\overline{b}) > 0$ for $\Delta_1 < \delta\Omega < \delta\Omega^1$, or $F(b)$ which is strictly increasing and convex with $F(\underline{b}) > 0$ and $F(\overline{b}) > 0$ for $\delta\Omega < \Delta_1$.

In these both cases, there exist two solutions b_1 and b_2 to the Eq. $F(b) = G(b)$ if there is a value of $b = b_0$ such that $F(b_0) < G(b_0)$.

Let $b_0 = \epsilon\overline{b} + (1-\epsilon)\underline{b}$, with $\epsilon \in (0,1)$. We deduce that:

$$\begin{aligned}
F(b_0) &\equiv [\epsilon\overline{b} + (1-\epsilon)\underline{b}](\omega+u)\{(\epsilon\overline{b} + (1-\epsilon)\underline{b})[\beta\mu(1-\delta\Omega(\beta+\gamma)) - \delta\Omega\gamma] \\
&\quad +u[(1-\delta\Omega)\gamma + \beta\mu(1-\delta\Omega(\beta+\gamma))]\} \\
G(b_0) &\equiv \delta\Omega(1-\beta\mu)[\epsilon\overline{b} + (1-\epsilon)\underline{b} + u]\epsilon(1-\epsilon)(\overline{b} - \underline{b})^2
\end{aligned}$$

Therefore, $G(b_0) > F(b_0)$ if:

$$\begin{aligned}
&\delta\Omega(1-\beta\mu)\epsilon(1-\epsilon)(\overline{b}-\underline{b})^2 \frac{\epsilon\overline{b} + (1-\epsilon)\underline{b} + u}{\epsilon\overline{b} + (1-\epsilon)\underline{b}} \\
&> (\omega+u)\{(\epsilon\overline{b} + (1-\epsilon)\underline{b})(\Delta_1 - \delta\Omega) + u(\Delta_0 - \delta\Omega)]\}[\gamma + \mu\beta(\beta+\gamma)]
\end{aligned}$$

This inequality is satisfied if Ω is higher, or lower and sufficiently close to Δ_1/δ, and u is sufficiently small. In this case, there are (at least) two steady states b_1 and b_2 such that $\underline{b} < b_1 < b_2 < \overline{b}$.

In contrast, if Ω is sufficiently small, this inequality is never satisfied, which means that $F(b)$ and $G(b)$ never cross and there is no steady state with bubble. This means that there exists $\Omega^0 > 0$ such that there is no steady state for $\Omega < \Omega^0$.

We proceed to study stability at each steady state. To this end, we first rewrite equations (36) and (37) as:

$$b_{t+1} = \frac{(1-\delta\Omega)[(\beta+\gamma)\omega - \alpha u_{t+1}](b_t + u_t)}{Den_t} \tag{D.3}$$

$$f_{t+1} = \frac{[(\beta+\gamma)\omega - \alpha u_{t+1}][f_t - \beta\mu(\omega + \delta\Omega f_t + u_t)]}{Den_t} \tag{D.4}$$

where

$$\begin{aligned}
Den_t &= [1-\delta\Omega(\beta+\gamma)]f_t + (1-\delta\Omega)(b_t+u_t) - \\
&\quad -(\omega + \delta\Omega f_t + u_t)[(1-\delta\Omega)\gamma + \beta\mu(1-\delta\Omega(\beta+\gamma))]
\end{aligned}$$

Equations (D.3) and (D.4) form a dynamic system that characterizes the equilibrium. To analyze the dynamics, we differentiate the dynamic system (D.3)-(D.4) with $u_t = u_{t+1} = u$ in the neighborhood of a steady state to obtain:

$$\begin{aligned}
&\frac{db_{t+1}}{b} = \frac{b}{b+u}\frac{\overline{b}-b}{\overline{b}}\frac{db_t}{b} \\
&-\frac{[1-\delta\Omega(\beta+\gamma)](1-\delta\Omega\beta\mu)-\delta\Omega(1-\delta\Omega)\gamma}{(1-\delta\Omega)(b+u)\overline{b}} fb\frac{df_t}{f} \qquad \text{(D.5)}\\
&\frac{df_{t+1}}{f} = -\frac{b^2}{(b+u)\overline{b}}\frac{db_t}{b} \\
&+\frac{(1-\delta\Omega\beta\mu)\overline{b}-[1-\delta\Omega(\beta+\gamma)](1-\delta\Omega\beta\mu)f+\delta\Omega(1-\delta\Omega)\gamma f}{(1-\delta\Omega)(b+u)\overline{b}} b\frac{df_t}{f}
\end{aligned} \tag{D.6}$$

The characteristic polynomial associated to this linearized system is given by $P(\lambda) = \lambda^2 - T\lambda + D = 0$, where T and D are the trace and the determinant of the associated Jacobian matrix. Using (38), (D.5) and (D.6), the determinant is given by:

$$D = \left(\frac{b}{b+u}\right)^2 \frac{\widetilde{D}}{(1-\delta\Omega)\overline{b}} \tag{D.7}$$

with

$$\begin{aligned}
\widetilde{D} &= (1-\delta\Omega\beta\mu)(\overline{b}-b) - [(1-\delta\Omega(\beta+\gamma))\delta\Omega(1-\beta\mu) \\
&\quad +(1-\delta\Omega)(1-\delta\Omega(\beta+2\gamma))]\frac{b\beta\mu(\omega+u)}{\delta\Omega(1-\beta\mu)(b-\underline{b})}
\end{aligned} \tag{D.8}$$

Using (D.7) and (D.8), the trace can be given by:

$$T = \frac{b+u}{b}D + \frac{b}{(b+u)(1-\delta\Omega)\overline{b}}[\overline{b}(1-\delta\Omega) + b\delta\Omega(1-\beta\mu)] \tag{D.9}$$

Using (43), we note that $\delta\Omega$ close to Δ_1 and u small mean that $F(b)$ is flat and small for $b \leqslant \max\{\overline{b}, b_2\}$. This implies that b_1 is close to $\underline{b}$ and b_2 close to $\overline{b}$. Using (42) and (44), it also implies that $(\overline{b}-b)(b-\underline{b})$ evaluated at each steady state is small. Using (D.8), we deduce that $\widetilde{D}(b-\underline{b})$ is strictly negative, because $(1-\delta\Omega(\beta+\gamma))\delta\Omega(1-\beta\mu) + (1-\delta\Omega)(1-\delta\Omega(\beta+2\gamma)) = \widehat{F}(\delta\Omega) > 0$ (see Eq. (D.2)). This means that $D < 0$.

Using (D.9), we have:

$$P(1) = 1 - T + D = \frac{u}{b}\left(\frac{b}{b+u} - D\right) - \frac{b^2}{(b+u)\overline{b}}\frac{\delta\Omega(1-\beta\mu)}{1-\delta\Omega} \tag{D.10}$$

We deduce that $P(1) < 0$ because we assume that u is small. Since $P(+\infty) = +\infty$, one eigenvalue is always strictly higher than one.

We now compute:

$$P(-1) = 1 + T + D = \frac{2b+u}{b}D + \frac{2b+u}{b+u} + \frac{b^2\delta\Omega(1-\beta\mu)}{(b+u)(1-\delta\Omega)\overline{b}} \tag{D.11}$$

Using (D.7) and (D.8), we easily see that when b tends to $\underline{b}$, D becomes strongly negative. We deduce that $P(-1) < 0$. By continuity, this also holds for $b = b_1$. Therefore, since $P(-\infty) = +\infty$, one eigenvalue is strictly smaller than -1, which means that b_1 is a source.

When b tends to $\overline{b}$, $P(-1) > 0$ is equivalent to:

$$\begin{gathered}[(1-\delta\Omega(\beta+\gamma))\delta\Omega(1-\beta\mu) + (1-\delta\Omega)(1-\delta\Omega(\beta+2\gamma))] \\ \frac{\beta\mu(\omega+u)}{\delta\Omega(1-\delta\Omega)(1-\beta\mu)(\overline{b}-\underline{b})}\frac{\overline{b}}{\overline{b}+u} < 1 + \frac{\overline{b}\delta\Omega(1-\beta\mu)}{(2\overline{b}+u)(1-\delta\Omega)}\end{gathered}$$

which is satisfied for μ low enough. By continuity, we have $P(-1) > 0$ for $b = b_2$. Since $P(0) = D < 0$, one eigenvalue belongs to the interval $(-1, 0)$. This means that b_2 is a saddle.

To prove Corollary 1, we replace u by zero in all equations. Note that $\underline{b} = 0$ and $\overline{b} = (\beta+\gamma)\omega$. The equation $F(b) = G(b)$ admits two solutions $b = 0$ and $b = \tilde{b}$, with

$$\tilde{b} = \frac{\omega\left[\delta\Omega(\beta+2\gamma) - \beta\mu\right]}{(1-\mu\beta)\delta\Omega}$$

$\tilde{b} > 0$ if and only if $\delta\Omega > \beta\mu/(\beta+2\gamma)$. Furthermore, note that

$$\overline{b} - \tilde{b} = (\Delta_1 - \delta\Omega)\,\frac{\gamma+\beta\mu(\beta+\gamma)}{(1-\mu\beta)\delta\Omega}\omega$$

If $\delta\Omega$ is close to Δ_1, then $\tilde{b}$ is close to $\overline{b}$. From the analysis of the dynamics when $u > 0$, we deduce that when $u = 0$ and $\delta\Omega$ close to Δ_1, the steady state $\tilde{b}$ has the same stability property as the steady state b_2. Thus, $\tilde{b}$ is a saddle.

E Proof of Proposition 2

We have $\partial F(b)/\partial\Omega < 0$, $\partial G(b)/\partial\Omega > 0$ if $b \in (\underline{b}, \overline{b})$ and $\partial G(b)/\partial\Omega < 0$ if $b > \overline{b}$. In addition, at the steady state b_1, we have $F'(b_1) < G'(b_1)$, and at the steady state b_2, $F'(b_2) > G'(b_2)$. We easily deduce that:

$$\frac{db_1}{d\Omega} = \frac{\partial G(b)/\partial\Omega - \partial F(b)/\partial\Omega}{F'(b_1) - G'(b_1)} < 0$$

because $b_1 \in (\underline{b}, \overline{b})$, and

$$\frac{db_2}{d\Omega} = \frac{\partial G(b)/\partial\Omega - \partial F(b)/\partial\Omega}{F'(b_2) - G'(b_2)} > 0$$

if b_2 belongs to $(\underline{b}, \overline{b})$ or b_2 is higher but close to $\overline{b}$. According to the proof of Proposition 1, this occurs if $\Omega < \Delta_1/\delta$ or if Ω is higher but close to Δ_1/δ and u is sufficiently small.

We use (38) to obtain

$$\frac{df}{d\Omega} = -\frac{\delta f^2}{b\mu\beta(\omega+u)}\left[\frac{u}{b}\left(1-\delta\Omega\right)\frac{db}{d\Omega} + b\left(1-\mu\beta\right) + u\right] < 0$$

when u is sufficiently small.

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