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Mark Carlson
Board of Governors of the Federal Reserve

Galina Hale
Yale University.

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Mark Carlson*

Board of Governors of the Federal Reserve

Galina Hale†

Yale University.

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Abstract

With the rise of international bond markets in the 1990s, the role of sovereign credit ratings has become increasingly important. In the aftermath of Asian Crises a series of empirical studies on the effects of sovereign ratings appeared. The theoretical literature on the topic, however, remains rather scarce. We propose a model of rating agencies that is an application of global game theory in which heterogeneous investors act strategically. The model is consistent with the main findings of the empirical literature. In particular, it is able to explain the independent effect of sovereign ratings on the cost of debt. Our model also predicts that, in addition to affecting the level of debt roll–over, the mere existence of the rating agency's announcement can increase the magnitude of the response of capital flows to changes in fundamentals. In addition, introducing a rating agency to a market that otherwise would have the unique equilibrium can bring multiple equilibria. The model also allows us to explore the reasons why agencies may over–react to crises, how they can spread financial contagion, and the failure of rating agencies to predict crises.

JEL classification: F34, G14, G15

Key words: credit rating, rating agency, sovereign debt, global game

*Board of Governors of the Federal Reserve. Contact: Mark.A.Carlson@frb.gov.

†Corresponding author. Department of Economics, Yale University. Contact: galina.hale@yale.edu.
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1 Introduction

"By attaining a sovereign credit rating, your country will help reduce risk and encourage investment. A sovereign credit rating gives courage to capital." Secretary Colin L. Powell. Washington, DC. April 23, 2002.

Credit rating agencies have played an increasingly important role in international capital markets by gathering information that would not be available to investors and helping these investors assess the economic strength and likelihood of default of international borrowers. This is particularly true for sovereign borrowers: the number of countries that have received a credit rating increased from about a dozen in 1980 to about a hundred in 2002.[1] Wider use of credit ratings has likely increased sovereign governments' access to capital markets and improved their ability to raise funds.[2]

The increased use of credit ratings, however, is not without controversy. On occasion, countries have argued that credit rating agencies have provided incorrect assessments of their likelihood of default and thus increased their borrowing costs.[3] Following the crisis in East Asia, some market participants and scholars argued that changes in ratings exacerbated the crisis (Ferri, Liu, and Stiglitz 1999, Reisen and von Maltzan 1998). Recent empirical work has established a number of stylized fact regarding the effects of credit ratings on financial markets: however, to the best of our knowledge, the existing theoretical models do not provide a framework for putting all these facts together. In this paper, we take a step towards filling this gap by applying recently developed theory of coordination amongst investors to better understand the effects rating agencies might have on the equilibrium. We then reconcile our model predictions with the stylized facts.

The empirical literature has found that rating agencies have affected financial markets in a variety of ways. One of the basic findings is that credit ratings have an effect on the yield of sovereign bonds above and beyond the effect of economic fundamentals, even though changes in credit ratings

[1]As of today, Moody's and Standard and Poors provide ratings for over 100 countries each, while twenty years ago only 11 sovereigns were rated by Standard and Poors (Ferri, Liu, and Majnoni 2000).

[2]See International Monetary Fund (1999) *International Capital Markets: Developments, Prospects and Key Policy Issues.* The Fund reports that a number of institutional investors are constrained to hold only securities that have been rated as investment grade. Thus having a credit rating is a necessary prerequisite to interacting with these investors. Further, the Fund suggests that rating agencies reduce the costs associated with gathering information and thus boost the number of investors willing to enter some markets.

[3]See "Japan Rebukes Ratings Agencies For Falling Grades," Wall Street Journal. May 13, 2002, page C1.

are determined in large part by fundamentals (Cantor and Packer 1996, Clark and Lakshmi 2003, Kaminsky and Schmukler 2002). Further, changes in credit ratings affect financial markets even though empirical research has also found that changes in the yields on sovereign bonds generally start to move prior to a ratings change rather than after a ratings change has been announced (Cantor and Packer 1996, Mora 2004). Thus, ratings appear to have an effect even though there is some question about whether changes in ratings provide timely information. Concerns about the timeliness of the information provided by rating agencies is most apparent around economic crises when some scholars have found that ratings decline after the crisis has occurred rather than prior to it (Reinhart 2002, Reisen and von Maltzan 1998).

While there has been some theoretical work on rating agencies, the analysis done thus far (again, to the best of our knowledge) does not address all the stylized facts uncovered by the empirical research. In their foundational work, Millon and Thakor (1985) formulate a model which, using information asymmetries, explains why rating agencies should exist even if they deal with the same economic fundamentals as investors. However, it is not clear in their model why investors should react to both news about fundamentals and the rating agency's response to the news. Boot and Milbourn (2002) present a model in which rating agencies act as market coordination mechanisms which can be used to discipline firms; however, the way that economic fundamentals interact with rating agencies is not clear.[4]

In this paper, we apply a global game model, developed in work such as Morris and Shin (2003) and Goldstein and Pauzner (2003), to analyze the effects of sovereign credit ratings,[5] and show that it can help explain the stylized facts uncovered in the empirical work. In the model, investors receive imperfect and heterogeneous private information regarding the ability of a sovereign to repay its debt as well as the credit rating agency's assessment of the sovereign's creditworthiness. Investors incorporate the agency's assessment of the economy into their own forecast; thus, the agency provides a focal point toward which the investors' beliefs gravitate. As a result, the agency affects the amount of debt the sovereign is able to roll-over and the probability of default.

[4] More precisely, a particular firm's fundamentals do not necessarily affect the equilibrium in which it ends up after the rating agency makes its announcement.

[5] While this paper is written with sovereign debt ratings in mind and some issues may be specific to these markets, the general structure of the model is more widely applicable.

We show that even if credit ratings are influenced by the same fundamentals as investors' private information, ratings will still affect investors' decisions. Credit ratings have this effect because the revision of the rating agency's signal in response to changes in fundamentals causes investors to revise their expectation regarding what other investors will do. Thus, we show that a global games model is able to explain the main stylized fact about the effects of credit rating agencies. Further, some simple extensions of the model allow us to explore other empirical findings, such as spill-overs to other borrowers (Gande and Parsley 2002, Kaminsky and Schmukler 2002) and possible excessively large revisions to credit ratings in response to changes in fundamentals by the rating agency during economic booms and busts (Ferri, Liu, and Stiglitz 1999),[6] that the existing theoretical literature has difficulty explaining.

The model also predicts that rating agencies will have some effects on financial markets that have not been tested for in empirical studies. For instance, our model suggests that the addition of the rating agency increases the magnitude of the response of the capital flows to changes in fundamentals, thus providing a rationale for the anecdotal complaints about the increased volatility of capital flows that have accompanied the rising use of sovereign credit ratings. It may also be related to the (Calvo 1998) argument that a market coordination mechanism may lead to a "sudden stop" in the flow of funds to sovereign borrowers and precipitate a crisis.

To be clear, this paper is primarily an application of the global games framework to a particular situation and whose purpose is to show how these models can be useful in understanding the role rating agencies play in financial markets and in explaining a variety of the stylized facts uncovered by empirical research. We also find that this framework suggests that there are trade-offs associated with the use of credit rating agencies, such as increased market volatility in response to changing fundamentals, that have not previously been identified theoretically or empirically. Thus our paper illustrates how the growing body of theoretical literature research involving higher order beliefs can be quite helpful in understanding specific problems and situations.

The paper is organized as follows. In part two, we summarize up–to–date empirical findings on the impacts of sovereign credit ratings and discuss potential explanations. Part three develops a

[6] The hypothesis that ratings agencies over-reacted during booms and busts is undecided in the empirical literature. For instance, Mora (2004) argues that rating agencies did not over-react.

model of debt roll–over with a rating agency. In part four, we show how the introduction of a rating agency into a global game framework can help explain stylized facts and discuss further implications and extensions of the model. Part five concludes.

2 Stylized facts

In this section, we summarize recent research on the relationships between economic fundamentals, sovereign credit ratings, and financial markets. Rather than reviewing the literature chronologically, we group the papers by their findings to formulate stylized facts.

Both markets and credit ratings respond to fundamentals. The response of investment to fundamentals has been well documented (Corbo and Hernandez 2001, Montiel and Reinhart 1999). Cantor and Packer (1996) show that over 90 percent of the variation in sovereign credit ratings can be explained by publicly observed fundamentals.

Changes in credit ratings tend to follow movements in markets rather than precede them. Empirical studies (Cantor and Packer 1996, Kaminsky and Schmukler 2002, Larrain, Reisen, and von Maltzan 1997) have found that most ratings changes tend to occur in the midst of movements in financial markets. Downgrades in credit ratings tend to occur in the midst of a rise in spread of the yield on sovereign bonds over the yield on U.S. securities, while upgrades generally occur during a fall in spreads. The tendency of credit ratings to follow markets may be most extreme during financial crises. If ratings provide up-to-the-moment information, one would expect that the ratings on sovereign bonds would decline prior to the onset of a financial crisis. However, Reinhart (2002) finds that rating downgrades tend to follow financial crises than precede them.

Markets respond to changes in credit ratings. Despite the findings that credit ratings tend to respond to the same information available to markets and follow movements in markets rather than anticipate them, empirical studies have found that changes in credit ratings still have an independent influence on the yields on sovereign bonds. Cantor and Packer (1996) find such a result using panel regressions. Clark and Lakshmi (2003) find evidence of the impact of credit ratings in careful examination of factors affecting movements in the yields on Indian bonds. Ammer (1998) also concludes that sovereign bonds have an impact on bond yields, with the strongest reaction being for downgrades and for sovereigns with speculative grade ratings. Kaminsky and Schmukler (2002) find that ratings changes are one type of news event that causes reactions in markets.

Contagious effects of changes in credit ratings. Empirical research has found that movements in sovereign credit ratings not only have effects on the yields on the sovereign debt for which they are issued, but also on other financial markets within the country and also on financial markets in other countries. Kaminsky and Schmukler (2002) find that changes in the credit rating on a country's sovereign bonds also affects the country's stock price indices. Gande and Parsley (2002) find that negative rating events increase interest rate spreads on sovereign bonds in nearby countries. Kraussl (2003) finds that sovereign credit rating changes have effects on both bond yield spreads and short-term international liquidity positions.

Credit rating agencies may have over-reacted following the Asian Crisis. Some scholars (Ferri, Liu, and Stiglitz 1999, Reisen and von Maltzan 1998) have argued that rating agencies were excessively optimistic preceding the Asian crisis in 1998 and excessively pessimistic following them. They note that there were sudden large drops in ratings for several countries following the 1998 crisis in East Asia. However, (Mora 2004) finds that rating agencies did not change their ratings excessively, and that ratings were in line with fundamentals, she argues that the perceived overreaction may be due to the tendency of credit ratings to lag markets.

We now turn to presenting a model and return to these stylized facts in part four to see if we can explain them using the framework of our model.

3 Model

In this section, we develop a model in which a credit rating agency acts as a focal point in a coordination game among investors. We start by developing a benchmark model without a credit rating agency in which imperfectly informed investors decide whether to roll over the debt of a sovereign government based on their own assessments of the sovereign's ability to repay and on their expectations of the actions of the other investors. This model is a basic version of a global game model, as described in Morris and Shin (2004). We then introduce the credit rating agency which provides a public assessment of the sovereign's creditworthiness. With this model, we are able to assess the effect of the rating agency on the equilibrium, both in terms of the effect on the level of debt and the effect on how the equilibrium changes in response to shifts in the sovereign's ability to pay. We also show that the model leads to several predictions not yet investigated by empirical or theoretical studies, notably that the introduction of rating agencies increases market volatility.

We assume that the sovereign government has an outstanding amount of one period debt that it wishes to rollover. We normalize the size of this stock to be equal to 1. The government debt is held by N risk–neutral investors with mass c each, thus $Nc = 1$. The government can and is willing to repay an exogenous share θ of this debt while the remaining amount of debt $(1-\theta)$ needs to be rolled over.[7] Each investor decides individually whether or not to roll over her unit of debt and there is no cooperation among investors.[8] Denote investor i's decision d_i: $d_i = 1$ if investor i decides to roll over her unit of debt and $d_i = 0$ otherwise. The total amount of debt that will be rolled over is then

$$D = c \sum_{i=1}^{N} d_i,$$

which implies that $D \in [0, 1]$.

If the investor decides not to roll over her unit of debt, she can withdraw it without any premium

[7] One can think of θ as a measure of fundamentals. Stronger fundamentals lead to more economic growth providing the government with a larger revenue base to use to repay the debt.

[8] To keep the emphasis of the paper on the rating agency, we do not discuss bargaining or cooperation between the government and investors, or among the investors. See (Bulow and Rogoff 1989) for a model with bargaining. The assumption that debt roll–over is financed by investors that currently hold the stock of debt is not essential. The model can be easily reinterpreted for the case when new investors choose between sovereign debt and risk–free assets.

or punishment and invest it in a risk–free asset with gross return normalized to 1.[9] If she decides to roll over her debt, she forgoes the opportunity of withdrawing money and investing in a risk–free assets and instead receives a gross return of $R > 1$ if there is no default.[10] This gross rate of return implies that risk premium is $R - 1$. If an insufficient number of investors roll over their debt holdings, i.e. $D < 1 - \theta$, the country is forced to default on its debt and none of the investors that rolled over their holdings of debt are paid.[11] Thus, the payoff structure for investors is as follows:

$$u_i(d_i, d_{-i}, \theta) = \begin{cases} R & \text{if } d_i = 1 \text{ \& } D \geq (1 - \theta) \\ 0 & \text{if } d_i = 1 \text{ \& } D < (1 - \theta) \\ 1 & \text{if } d_i = 0 \end{cases} \tag{1}$$

This payoff structure implies that investors will choose to roll over the debt if and only if they believe that

$$\text{Prob}(D \geq 1 - \theta) R \geq 1. \tag{2}$$

Suppose that at the time of the investors' roll–over decisions θ is not known. Assume however, that it is public knowledge that the realization will be drawn from normal distribution with mean $\bar{\theta}$ and standard deviation σ. The *apriori* probability $1 - p$ of being repayed is

$$1 - p = \text{Prob}(D \geq 1 - \theta) = \Phi(\frac{1}{\sigma}(D - 1 - \bar{\theta})), \tag{3}$$

where Φ is standard normal CDF, and p is the probability of default.

Our assumptions imply that if $\theta < 0$, there will be a default unless "new money" is injected. In our model, we do not allow for this possibility, therefore there will always be default if $\theta < 0$, and

[9] In this model we assume that those who want to withdraw their money can always do it before the draw of θ occurs. We will not focus on how this is financed. In our model it is implicit that default is not economically desirable, which is in contrast with Chang (2002).

[10] Again, we do not specify how the premium is financed. Presumably economic growth, as reflected by θ, would allow the country to repay part of the debt while the remainder is financed by future debt rollovers. This is sustainable as long as the growth of revenue is greater than or equal to the growth of interest payments. It would probably be more realistic to assume that θ falls as R rises, however this complicates the model without adding any insight.

[11] This implicitly assumes that a country bears costs of default that are fixed and independent of the amount of debt defaulted, and that the country does not build long–run relationships with investors. Under these conditions it will be optimal for the country to always default on the entire debt stock.

therefore not rolling over the debt $d = 0$ is a dominant strategy for every investor. Likewise, if $\theta > 1$, the default will not occur even if $D = 0$, because the government can repay all the debt from its own resources, thus rolling over the debt $d = 1$ is a dominant strategy in this case. We focus our attention on the equilibria with $\theta \in (0; 1)$, which will depend on the information structure regarding θ, however, as shown in Morris and Shin (2003), the dominance regions described are necessary for the existence of the unique equilibrium.

For simplicity, we will restrict our attention to pure strategy equilibria, although the general results of the paper still hold if mixed strategies are allowed. We also assume that $N \to \infty$ and analyze the version of the model with continuum of investors with mass 1.[12]

3.1 Full information

If the share of debt that the government can repay, θ, is common knowledge to all investors, then there are two symmetric equilibria in which either $D = 0$ or $D = 1$. Both are self–fulfilling and can occur at any level of $\theta \in (0; 1)$. There are also infinitely many non–symmetric equilibria (Morris and Shin 2004). This multiplicity will disappear as we introduce imperfect heterogeneous signals and strategic behavior.[13]

This perfect information set–up is frequently a benchmark model for thinking about the investor coordination. One might think that with perfect information the role of credit rating agencies would be to help investors coordinate on one of the two equilibria, which then implies that credit rating agencies could be responsible for swings in international capital flows. We will see from the model below that some of this coordination effect is present when we allow for imperfect information and heterogeneous beliefs. However, this multiple equilibria model does not help us understand the stylized facts described in the previous section. We now turn to the model with a unique equilibrium.

[12] For a model with big players, see Corsetti, Dasgupta, Shin, and Morris (2004).

[13] The same logic applies if all investors get the same noisy signal about θ, and this signal is common knowledge.

3.2 Private signals

Suppose now that in addition to their common prior about $\theta \sim N(\bar{\theta}, \sigma)$, investors get private noisy signals about θ. Denote investors i's signal $\tilde{\theta}_i$:

$$\tilde{\theta}_i = \theta + \varepsilon_i, \quad \varepsilon_i \sim N\left(0; \frac{1}{\beta}\right),$$

where β is the "precision" of private signal. We will assume that only investor i observes her signal $\tilde{\theta}_i$, while β is common knowledge. This gives investor i's posterior belief about θ, θ_i:

$$\theta_i \sim N\left(\frac{\bar{\theta} + \beta\tilde{\theta}_i}{\gamma + \beta}, \frac{1}{\gamma + \beta}\right),$$

where we denoted the precision of the prior $1/\sigma$ as γ.

This posterior distribution of beliefs about θ gives us a unique equilibrium if private signals are sufficiently informative as compared to the prior, $\beta \geq \frac{\gamma^2}{2\pi}$.[14] In what follows, we assume that this condition holds.

The unique equilibrium can then be described by the threshold level of θ below which there will be a default in equilibrium, because fewer than $1 - \theta$ investors will choose to roll over their debt. Above that level, a sufficient number of investors will choose to roll over the debt and there will be no default. This unique level of θ should then be consistent with the belief of a pivotal investor who is indifferent between rolling over debt and not doing so. We denote this equilibrium threshold of θ as θ^*. The equilibrium in this model, θ^*, is a switching point such that the fundamental $\theta \geq \theta^*$ results in a successful roll–over, while $\theta < \theta^*$ results in default.[15]

Proposition 1 *(Morris and Shin 2004) Given the information structure above, and if $\beta \geq \frac{\gamma^2}{2\pi}$, the equilibrium is unique and θ^* is implicitly determined by*

$$\theta^* = \Phi\left(\frac{1}{\sqrt{\beta}} \left[\gamma(\theta^* - \bar{\theta}) + \sqrt{\gamma + \beta}\, \Phi^{-1}\left(\frac{1}{R}\right)\right]\right) \tag{4}$$

[14] See Morris and Shin (2004) for the proof in a similar setting.

[15] Since for any $0 < \theta < \theta^*$ there will be default in equilibrium, and this default would not occur if all investors could coordinate on rolling over the debt, θ^* could be interpreted as a measure of inefficiency due to coordination failure.

and is $\in (0;1)$*. In addition,* $\partial\theta^*/\partial\bar{\theta} < 0$*,* $\partial\theta^*/\partial R < 0$*.*

Proof. Follows from Morris and Shin (2004) with α replaced by γ. Signs of the derivatives are obvious.

For convenience, we will denote $\Phi^{-1}\left(\frac{1}{R}\right)$ as ρ in what follows. It will be useful to keep in mind that $\rho > 0 \Leftrightarrow R \in (1;2)$ and $\rho < 0 \Leftrightarrow R > 2$. We can also establish the following necessary and sufficient condition:

Proposition 2 $\partial\theta^*/\partial\beta < 0$ *if and only if*

$$\bar{\theta} < \frac{\rho}{\sqrt{\gamma+\beta}} + \Phi\left(\sqrt{\frac{\beta}{\gamma+\beta}}\ \rho\right), \tag{5}$$

Which implies the following sufficient conditions:

1. If $\rho > 0$ *and* $\bar{\theta} < \Phi\left(\sqrt{\frac{\beta}{\gamma+\beta}}\ \rho\right)$*,* $\partial\theta^*/\partial\beta < 0$*.*

2. If $\rho < 0$ *and* $\bar{\theta} > \Phi\left(\sqrt{\frac{\beta}{\gamma+\beta}}\ \rho\right)$*,* $\partial\theta^*/\partial\beta > 0$*.*

Proof. See Appendix.

We are most interested in the actual probability of default, p^*. This is equal to the probability that actual θ will be below the threshold θ^*.

$$p^* = \text{Prob}\,(\theta < \theta^*) = F_\theta(\theta^*) = \Phi(\gamma(\theta^* - \bar{\theta})),$$

which is monotonically increasing in θ^*. Therefore for any variable $\bullet$, $\text{sign}\,(\partial\theta^*/\partial\bullet) = \text{sign}\,(\partial p^*/\partial\bullet)$.

We can see from Proposition 1 that the probability of default is lower if $\bar{\theta}$ is higher and if R is higher. Both better fundamentals and a higher risk premium on sovereign debt increase the incentives to rolling over the debt and therefore more investors choose to do so, which in turn lowers the probability of default.

Proposition 2 establishes the effects of precision of private signals on probability of default. The sufficient conditions present two interesting cases. In Case 1, interest rates are low while the fundamentals are relatively poor, which could happen if the interest rates were preset and then the (expected) fundamentals have worsened. In this case, higher precision of private information lowers the probability of default. In the absence of the coordination problem, the investors will

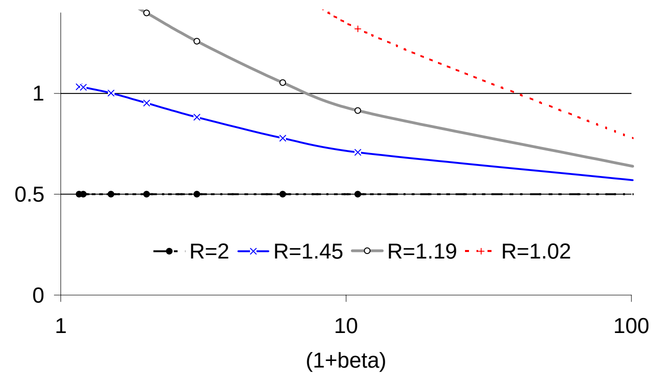


Figure 1: Right–hand side of equation (5) with $\gamma = 1$

be hesitant to roll over the debt. However, with more precise private information, investors would put less weight on public information ($\bar{\theta}$, which is low and is therefore bad news) and are therefore more likely to invest.

In Case 2, interest rates are extremely high (gross interest rate $R > 2$, which implies risk premium of over 100 percentage points), however, expected fundamentals are decent. In this case, each investor has a strong incentive to roll over the debt. More precise private information makes investors pay less attention to the public signal (which is good in this case) and therefore makes them less likely to invest, thus raising the probability of default.[16]

For the rest of the paper we assume that $\rho > 0$ ($R < 2$). Figure 1 shows the sufficient condition for $\partial\theta^*/\partial\beta < 0$ for several values of R. The region below each line indicates the values of $\bar{\theta}$ for which the condition holds. We can see that equation (5) is more likely to hold for smaller β, implying that an increase in the precision of the private signals typically lowers the probability of default unless the private signals are already quite precise.

[16]For further discussion of the intuition behind the effects of precision of public and private information, see Morris and Shin (2002) and Metz (2002).

3.3 The rating agency

In this section we introduce the rating agency and then show how it affects the equilibrium.

3.3.1 Model with a rating agency

Suppose now that there is a rating agency that has the same prior as all the investors and receives a signal $\tilde{\theta}^A$ with noise ν.[17]

$$\tilde{\theta}^A = \theta + \nu, \qquad \nu \sim N\left(0, \frac{1}{\alpha}\right).$$

We will assume that only the rating agency observes $\tilde{\theta}^A$ but α is common knowledge. Suppose that the agency directly announces $\tilde{\theta}^A$ and investors then update their prior accordingly. The new prior has mean

$$\theta^A \equiv \frac{\gamma\,\bar{\theta} + \alpha\,\tilde{\theta}^A}{\gamma + \alpha}$$

and variance $1/(\gamma + \alpha)$. We will assume that investors get the same private signals as before, and therefore the new posterior beliefs θ_i^A are distributed

$$\theta_i^A \sim N\left(\frac{\gamma\,\bar{\theta} + \alpha\,\tilde{\theta}^A + \beta\,\tilde{\theta}_i}{\gamma + \alpha + \beta}, \frac{1}{\gamma + \alpha + \beta}\right). \tag{6}$$

Now for the equilibrium to be unique, we have to impose a stricter condition on β. While before it was necessary and sufficient that $\beta \geq \frac{\gamma^2}{2\pi}$, now it is necessary that $\beta \geq \frac{(\gamma+\alpha)^2}{2\pi} > \frac{\gamma^2}{2\pi}$ if $\alpha > 0$. This gives us the first effect that introducing rating agency can have:

Proposition 3 *For $\beta \in \left[\frac{\gamma^2}{2\pi}, \frac{(\gamma+\alpha)^2}{2\pi}\right)$, there is a unique equilibrium in the absence of a rating agency and multiple equilibria if a rating agency is introduced.*

Proof. Follows from Morris and Shin (2004) with α replaced by $\gamma + \alpha$.

In other words, if private signals are precise enough to ensure uniqueness of equilibrium in the absence of a rating agency, but not precise enough relative to the precision of the agency's signal, introducing a rating agency will lead to a multiplicity of equilibria. In particular both $D = 0$ (default) and $D = 1$ (no default) symmetric equilibria will exist, which is similar to the full

[17] The three rating agencies report that they base their rating largely on economic fundamentals (Fitch 1998, Moody's 1999, Standard and Poor's 2002).

information case. For the remainder of this section, we will focus on the case where a unique equilibrium exists, i.e. $\beta \geq \frac{(\gamma+\alpha)^2}{2\pi}$. We will return to the issue of multiplicity in section 3.4.

Proposition 4 *(Morris and Shin 2004) Given the information structure above and* $\beta \geq \frac{(\gamma+\alpha)^2}{2\pi}$, *the equilibrium is unique and* θ^{A*} *is implicitly determined by*

$$\theta^{A*} = \Phi\left(\frac{1}{\sqrt{\beta}}\ \left((\gamma+\alpha)\theta^{A*} - \gamma\,\bar{\theta} - \alpha\,\tilde{\theta}^{A} + \sqrt{\gamma+\alpha+\beta}\ \rho\right)\right) \tag{7}$$

and is $\in (0;1)$. *In addition,* $\partial\theta^{A*}/\partial\tilde{\theta}^{A} < 0$, $\partial\theta^{A*}/\partial\bar{\theta} < 0$, $\partial\theta^{A*}/\partial R < 0$.

Proof. Follows from Morris and Shin (2004) with α replaced by $\gamma + \alpha$. Signs of derivatives are obvious.

Because the rating agency provides public information that investors use to determine the actions of other investors, we have a unique equilibrium in which both the rating agency and investors are influenced by economic fundamentals, yet the equilibrium is still affected by changes in the credit rating.

We can see that as before, the probability of default is lower if the prior mean of θ, $\bar{\theta}$, is higher or the risk premium R is higher. In addition, a better announcement by the agency lowers the probability of default, as expected. We will now analyze this equilibrium to see the effects of introducing a rating agency to the market where there was not one before.

3.3.2 Effects of rating agency on equilibrium

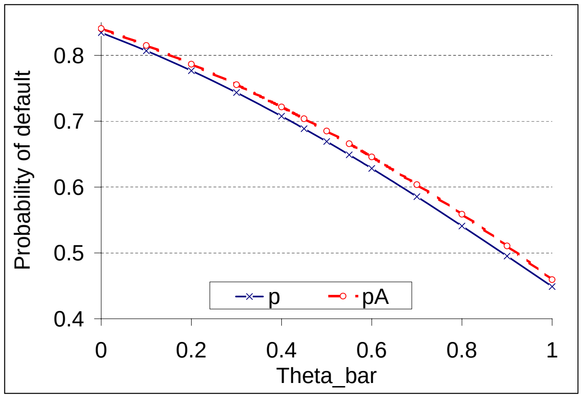
We can examine how the rating agency affects the equilibrium in two ways — through its effect on the mean of the new common prior for a given level of fundamentals and through its effect on the magnitude of the change in the equilibrium following a change in fundamentals.

First, a higher rating clearly leads to a "better" equilibrium, however the following is true:

Proposition 5 $\theta^{A*} \leq \theta^*$ *if and only if* $\tilde{\theta}^{A} \geq \theta^* + W$, *where* $W = \frac{\sqrt{\gamma+\alpha+\beta}-\sqrt{\gamma+\beta}}{\alpha}\ \rho$ *and is positive for* $\rho > 0$ *and* $\alpha > 0$.

Proof. See Appendix.

In other words, the rating agency equilibrium (weakly) dominates the equilibrium without the



Note: $\gamma = 1$, $\alpha = 1$, $\beta = 2$, $R = 1.2$, $\tilde{\theta}^A = \bar{\theta}$.

Figure 2: Effect of a change in $\bar{\theta}$ with and without the agency.

agency if and only if the signal that the agency gets is sufficiently better than the threshold level of θ in equilibrium without the agency. The wedge W is positive as long as rating agency's signal is somewhat informative ($\alpha > 0$) and the interest rate is not too high $R < 2$. See illustration on Figure 2.

Second, it has also been argued that rating agencies affect the volatility of capital flows. One way to examine how rating agencies affect the magnitude of the change in the equilibrium due to a change in fundamentals in our model, is to see how introducing a rating agency affects the response of the share of investors who choose to roll over the debt to changes in fundamentals: $\partial D/\partial\bar{\theta}$. The equilibrium share of investors who choose to roll over their debt is $D^{A*} = 1 - \theta^{A*}$ with agency and $D^* = 1 - \theta^*$ without.[18] Thus, $\partial D^*/\partial\bar{\theta} = -\partial\theta^*/\partial\bar{\theta}$ and $\partial D^{A*}/\partial\bar{\theta} = -\partial\theta^{A*}/\partial\bar{\theta}$.

Proposition 6 *If on average $\partial\tilde{\theta}^A/\partial\bar{\theta} = 1$, $\partial D^{A*}/\partial\bar{\theta} > \partial D^*/\partial\bar{\theta}$ at a point where $\theta^* = \theta^{A^*}$.*

Proof. See Appendix.

In other words, the introduction of a rating agency increases the magnitude of the response of capital flows to changes in fundamentals. This suggests that the rating agency may increase the volatility of capital flows if fundamentals are volatile. This occurs because investors put some

[18]Default occurs if $D < 1 - \theta$. Thresholds θ^* and θ^{A*} are such that for any θ lower than threshold, there will be default, and there will be no default for θ above the threshold. Thus, by definition, default occurs if $1 - \theta$ is above $1 - \theta^* = D^*$ (or $1 - \theta^{A*} = D^{A*}$).

weight on the agency's announcement, which is public information and is the same for everyone, and put lower weight on their own private signals. As a result, the posterior distribution of beliefs tightens and the same change in fundamentals will induce a larger number of investors to change their minds regarding rolling over their holdings of the debt.

One might ask then, if rating agencies increase the probability of default and the volatility of capital flows, why should they exist? There are two important considerations one has to be aware of before jumping to a conclusion of this kind. First, these results are conditional on the uniqueness of the equilibrium. If introduction of a rating agency leads to multiplicity, these results will not apply. In the next section we discuss in detail the effects of such scenario. Second, we must emphasize that our model is not a full model of the contribution of the rating agency to financial markets. In fact, we omit a very important feature, the cost of gathering information. In the presence of costly information acquisition, the public signal provided by rating agencies may provide information to investors for whom private information is prohibitively expensive and thus increase the number of investors willing to participate in a particular market. Further, since such costs affect the payoffs to investors directly, as well as through their effect on α and β, they will have an effect on overall welfare that could be positive or negative. We leave aside the question of the costs of obtaining information in this paper, for we analyze it in another project.

3.3.3 Effects of the information quality on equilibrium

It is also interesting to know how the equilibrium is affected by changes in the precision of information. We can establish the following necessary and sufficient condition:

Proposition 7 $\partial\theta^{A*}/\partial\beta < 0$ *if and only if*

$$\theta^A = \frac{\gamma\,\bar{\theta} + \alpha\,\tilde{\theta}^A}{\gamma + \alpha} < \frac{\rho}{\sqrt{\gamma+\alpha+\beta}} + \Phi\left(\sqrt{\frac{\beta}{\gamma+\alpha+\beta}}\,\rho\right), \tag{8}$$

given that on average $\tilde{\theta}^A = \bar{\theta} = \theta^A$, $\partial\theta^{A*}/\partial\alpha < 0$ *on average if and only if*

$$\theta^A = \tilde{\theta}^A = \bar{\theta} > -\frac{\rho}{2\sqrt{\gamma+\alpha+\beta}} + \Phi\left(\frac{3(\gamma+\alpha)+2\beta}{2\sqrt{\beta(\gamma+\alpha+\beta)}}\,\rho\right), \tag{9}$$

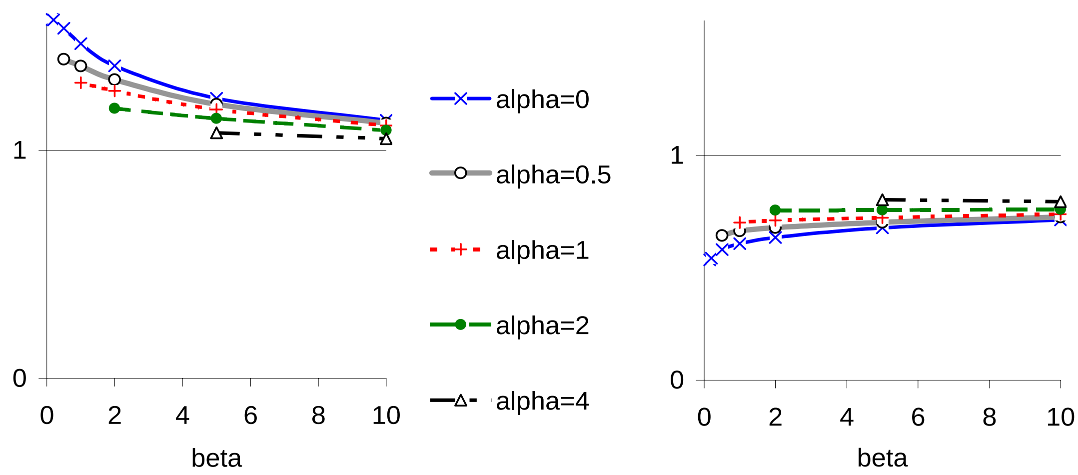


Figure 3: Right–hand side of equations (8) (left) and (9) (right) with $\rho = \gamma = 1$

Proof. See Appendix.

Note that the condition is now on θ^A, not $\bar{\theta}$. In most cases, equation (8) holds as can be seen from the left panel of Figure 3. This means that more precise private information most likely lowers the probability of default no matter what the rating agency's announcement, θ^A is, as long as it falls within the [0;1] interval that we are considering. Equation (9), in contrast, only holds if rating agency's announcement is relatively good (θ^A is high enough), as illustrated on the right panel of Figure 3: for the increased precision of the public information to reduce inefficiency, it is necessary that this information is positive, otherwise, increased precision will increase inefficiency and the probability of default. The intuition for both results is that relatively more precise public information makes investors disregard their private information thus worsening the inefficiency — the result shown with the linear action space setting in Morris and Shin (2002).

In other words, if rating agency's announcement is anything but very favorable, as it would be the case in crisis–prone countries, it is better if investors think that this announcement is quite noisy and rely on their own information. In fact, the higher the precision, the stronger is the requirement

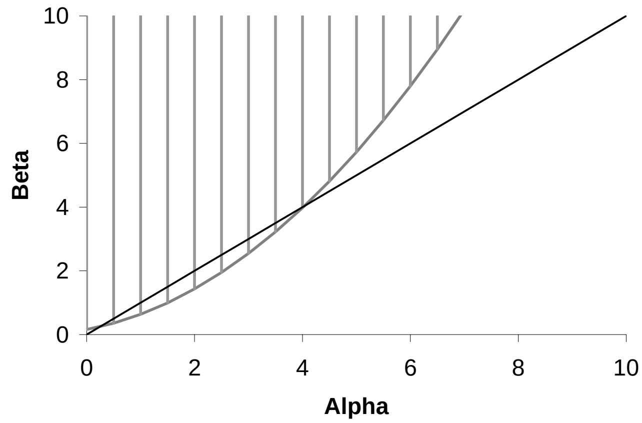


Figure 4: α, β and uniqueness condition (shaded area) for $\gamma = 1$

on θ^A for a marginal increase in precision to be beneficial. On Figure 3, it can be seen from the fact that constraints lines are higher for higher α.

3.4 Multiplicity versus uniqueness of equilibrium

In the previous section, we focused on the situation where the equilibrium was unique. In order to insure uniqueness, we had to assume that the condition on the precision of private signals relative to that of public information held, in particular, $\beta \geq (\gamma + \alpha)^2/2\pi$. This condition requires that private information be rather precise relative to the rating agency's information. In fact, as shown on Figure 4, if $\alpha \geq 4$, uniqueness requires that $\beta > \alpha$, i.e. private signals are more precise than public information.

If we think of the original common prior as easily available information, such as news media, it is not unrealistic to think that the information obtained by the analysts of rating agencies is much more precise. In this case, uniqueness will require that the private information that investors obtain is even more precise than that of the rating agency. This is not usually the way we think about the quality of information. The reason that investors make use of credit ratings is because they believe that rating agencies have better access to information and therefore their information is more accurate. Indeed, it does not matter whether the rating agency's information is more accurate in reality, what matters is the investors' beliefs about the precision of the rating agency's information.

Is it reasonable to think that uniqueness will be achieved without a rating agency, i.e. $\beta \geq \gamma^2/2\pi$? In order to answer this question we turn to our definition θ as the share of the debt that the government is able and willing to repay. Theoretically, it can take on any value on the real line — government is able to repay all of its debt and more ($\theta \geq 1$), or it might be in need of additional loans, beyond its need to roll over the debt ($\theta \leq 0$). In the first case, the country is certainly solvent, in the second, it is in default. If $0 < \theta < 1$, the country can only repay a share of the debt and, depending on the actions of investors, will or will not default. Investments in these countries could be thought of as speculative.

Assuming that all developing countries in all years draw theta from the same i.i.d. $N(\bar{\theta}, 1/\gamma)$, we can use the frequency of defaults and speculative grade ratings to calibrate the distribution of θ.[19] We focus on the short–term foreign currency rating, as it seems to be the most appropriate for our story. Out of 600 country–year ratings between 1983 and 2003 provided by Standard & Poors, 11 (2%) were in default, while 302 (50%) had a speculative grade.[20] We get similar numbers by restricting the calculations to just 10 years between 1993 and 2003.

Assuming that being in default implies $\theta < 0$ and having a speculative credit rating implies $0 < \theta < 1$, in terms of our distribution of θ the numbers above indicate that

$$\text{Prob}(\theta < 0) = \Phi\left(\gamma(0 - \bar{\theta})\right) = 0.02$$

and

$$\text{Prob}(0 < \bar{\theta} < 1) = \Phi\left(\gamma(1 - \bar{\theta})\right) - \Phi\left(\gamma(0 - \bar{\theta})\right) = 0.50,$$

which we can solve, using the values for inverse standard normal, to obtain $\bar{\theta} \simeq 0.97$ and $\gamma \simeq 2.1$, which implies $\gamma^2 \simeq 4.4$. Therefore uniqueness without a rating agency only requires $\beta > 0.7$, which means that private signals only need to be two–thirds as precise as the common prior. It

[19]The frequencies of default are roughly the same in the cross–section in 2003 and 2002, so obvious serial correlation in ratings does not affect our calibration here. We included all the countries that had ratings but US, Canada, Australia, New Zealand, Japan, EU-15 and offshore zones.

[20]We are not worried about the precision here — we are interested in the ballpark of the parameters.

is reasonable to believe that this condition is satisfied and private signals of investors (most of them are institutional investors if we talk about sovereign debt) are at least as precise as common prior, i.e. $\beta \geq 2.1$. In contrast, uniqueness with the rating agency requires *beta* to be greater than $(\alpha + 4.4)^2/2\pi$, which in many cases requires the precision of private signal to be significantly higher than that of rating agency. Arguably, this is not necessarily the case.[21]

Thus, while a unique equilibrium is easily achieved in the absence of a rating agency, it is much less likely to be achieved when a rating agency is introduced: even if the precision of a rating agency's signal is only as high as that of the common prior, uniqueness with a rating agency requires that private signal be almost three times as precise as the common prior. If uniqueness is not achieved, instead of the single equilibrium, there will be three: two stable equilibria and one unstable equilibrium. With multiple equilibria, the volatility of capital flows may be increased further as shifts in credit ratings may trigger jumps from one equilibrium to another.

The switch from a situation with a unique equilibrium to multiple equilibria due to the introduction of a rating agency is illustrated in Figure 5. Equilibrium E is the unique equilibrium in the absence of the rating agency. When the rating agency is introduced, the equilibrium will shift to either of the stable equilibrium (A or C) unless equilibrium E is exactly equal to the unstable equilibrium B. In the case illustrated in Figure 5, θ is high enough that the equilibrium converges to C, with a higher probability of default. This need not be the case in general. For some initial θ, the addition of the rating agency will shift the equilibrium to A, in which case the addition of the rating agency lowers the probability of default in equilibrium. In this latter scenario, moving from E to A, a credit rating indeed gives "courage" to capital. However, this improvement comes at a cost — changes in ratings may shift the equilibrium to the one with higher probability of default.

Furthermore, Angeletos, Hellwig, and Pavan (2003) show that allowing the rating agency to act strategically (while limiting its action space) might lead to multiple equilibria even if the condition on β is satisfied. This gives us an additional reason to believe that introducing a rating agency into

[21] The argument comparing the precision of investors' signals and the signal of the rating agency can go both ways: investors may know better about the instrument they invest in, given that money is at stake; on the other hand, rating agencies exist for the purpose of gathering and providing information to investors, thus there could be a moral hazard argument for investors not to seek precise information if they can rely on credit ratings. We do not need to take a stand on it to make an argument that unique equilibrium is less likely with the rating than without.

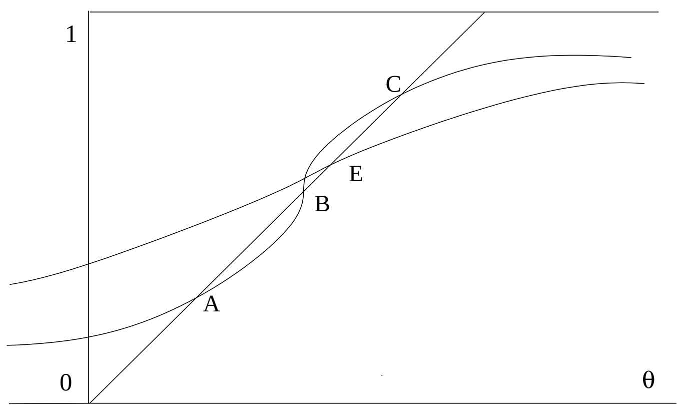


Figure 5: Equilibria (equations (4) and (7)) with and without a rating agency

a coordination game might bring back multiple equilibria.

4 Stylized facts revisited

As noted earlier, the model is able to explain several stylized facts. Most importantly, as shown in Proposition 4, the model indicates that the rating agency's announcement should have an independent effect, "above and beyond" the effect of fundamentals due to the fact that the credit rating is public information and therefore affects each investor's belief about other investors' beliefs. Even if the fundamentals $\bar{\theta}$ remained unchanged, the signal that the rating agency receives and therefore its announcement $\tilde{\theta}^A$ has an effect on θ^{A*}, and on the probability of default and the share of investors who will choose to roll over their debt.

While most empirical tests address the influence of credit ratings on the sovereign bond spreads, we fix the risk premium R. It is not determined within the model as part of equilibrium. One can interpret this risk premium (or spread) as set at the beginning of the period in consideration. At the end of the period, it is reasonable to assume that the risk premium will adjust according to the actual probability of default, that is, $R_{+1} = 1/(1 - p^A)$. Since a better announcement by the agency (higher $\tilde{\theta}^A$) lowers probability of default, it will lower the risk premium or spread the next period. Thus, a dynamic version of our model will generate a negative correlation between credit ratings and spreads, even if the fundamentals remain unchanged (in fact, even if the realization of fundamentals θ remain unchanged).

In the model, the rating agency announces its signal before the other agents act. However the intuition behind the model suggests that this effect of rating agencies would be the same in a setting in which time is continuous and investors are constantly making decisions about rolling over the debt. A change in the rating would still affect all investors' beliefs about the beliefs and likely actions of the other investors and thus would have an effect on financial markets.

4.1 Multiple countries and spill–over effects

As noted in Section 2, changes in ratings in one country have been found to have spill–over effects and cause changes in asset prices in other countries (Gande and Parsley 2002). Thus, rating agencies have been added to a growing list of channels by which events in one country affect neighboring countries.[22]

Our model suggests that there are two ways that this could occur. First, if the signals the agency receives about the two countries are linked,[23] then an event that causes a ratings change in one country could also cause a change in another country. To see this, suppose there are two countries: C and B, and country C is experiencing a crisis. If fundamentals (which in our case represent a country's ability and willingness to service its debt) are positively correlated across countries, the rating agency will get on average a "worse" signal about country B and therefore downgrade country B. This in turn will increase the probability of default in country B, since $\partial\theta^{A*}/\partial\tilde{\theta}^{A} < 0$, and will therefore provide an additional channel of contagion, beyond the effect of deteriorating fundamentals in country B.

Secondly, a rating agency can generate spill–over effects even if there are not any fundamental links between the countries. This will be the case if the rating agency fails to predict a crisis in country C. When investors learn about this, they update their beliefs about the precision of the rating agency's information. In particular, they will believe that α is lower than they previously thought. If previously the condition on the uniqueness of equilibrium was not satisfied, and country B was in a "good equilibrium", investors will start paying more attention to the private information

[22] Other channels include trade, financial markets, and political clubs. For discussion of those, see, for example, Glick and Rose (1999), Claessens, Dornbusch, and Park (2001), Pritsker (2001), Drazen (1999).

[23] Linked signals could be due to fundamental linkages between the countries, such as trade.

they have about country B, and the system may switch to the unique equilibrium. In this unique equilibrium, the probability of default is likely to be higher than in a "good" equilibrium. Notice that this will occur in the absence of a rating action by the agency. Thus, the credibility of a rating agency announcement could be another channel of financial contagion.

4.2 Excessive optimism and rating agencies' over–reaction

Ferri, Liu, and Stiglitz (1999) argued that rating agencies gave the Asian countries excessively high credit ratings prior to 1998 and excessively low ratings following the crisis. Reisen and von Maltzan (1998) also argue that the rating downgrades following the Asian crisis were excessive given the changes in fundamentals. On the other hand, Mora (2004) finds no evidence of over–reaction. Instead, she argues that rating agencies lag markets but generally have stable ratings.

Without taking a stand on whether rating agencies did over–react, our model provides some insight into how this situation might happen. Recall that the signal received by the agency is $\tilde{\theta}^A = \theta + \nu$, where we assumed that $\nu \sim N(0, 1/\alpha)$, with ν independently and identically distributed over time.

Agencies might prove "excessively optimistic" or "excessively pessimistic" if ν is not i.i.d., but instead is positively correlated with changes in θ. This might occur if preliminary estimates of fundamentals, such as productivity, are biased in a particular direction.

In this situation, countries which are growing and improving their fundamentals would experience even faster increases in their credit ratings. A sharp drop in fundamentals, as is likely to be the case following a crisis, would then lead to a negative ν and the rating agency would lower the credit rating by more than the change in "pure fundamentals" would indicate.

If this is the case, credit ratings would be procyclical and worsen lending cycles. This procyclicality of credit ratings is a concern under the Basel II accords as downgraded loans would require more capital and banks' ability to lend would be curtailed at times when monetary authorities are trying to ease financial conditions (Blum and Hellwig 1995, Carpenter, Whitesell, and Zakrajsek 2001).

4.3 Myopic rating agency and failure to predict crises.

One remaining stylized fact, is that rating agencies frequently do not downgrade sovereign debt prior to a crisis. With a slight extension our model provides some insight into why this might be.

In the above setup, rating agencies announce their beliefs about economic fundamentals. This is somewhat unrealistic, since rating agencies typically announce a rating that corresponds to the likelihood that the sovereign (or other borrower) will default. However, the equilibrium will be the same if investors know what the agency is doing, because investors can always back out $\bar{\theta}^A$ on which the announcement of the probability is made. However, it is possible that rating agencies do not take the coordination problem into account when making their rating announcements.

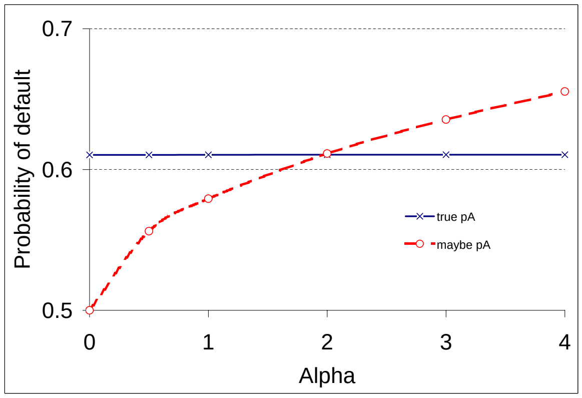
We can imagine that the rating agency, instead of having in mind the coordination game that we just described, has in mind the multiple equilibria model like the one we described in section 3.1. Suppose the agency announces the probability that there might be default, i.e. the probability that $\theta < 1$ and government cannot repay without any debt roll-over. We denote this probability p^M. Agency gets signal $\tilde{\theta}^A = \theta + \nu$ as before, therefore

$$p^M = \text{Prob}(\theta < 1) = \text{Prob}(\nu > \tilde{\theta}^A - 1) = 1 - F_\nu(\tilde{\theta}^A - 1) = 1 - \Phi(\sqrt{\alpha}(\tilde{\theta}^A - 1)).$$

Note that for $\tilde{\theta}^A < 1$ this probability is higher if α is smaller, i.e. the agency is more worried about the default if its information is more precise, which makes sense, since more precise information implies that distribution has thinner tails. The effect is the opposite for $\tilde{\theta}^A > 1$, however, it is less relevant when we talk about financial crises.

As Figure 6 illustrates, the myopic rating agency will be likely to underestimate the probability of default if its signal is not very precise.[24] It also implies that ratings will be more volatile as a result of changes in the quality of information if the rating agency is myopic than if the rating agency takes into account the coordination game. Since the rating agencies claim that the stability of the ratings is one of their goals (Mann and Cantor 2004), taking into account the coordination game

[24]We set $\bar{\theta} = \tilde{\theta}^A$ to a somewhat low value and R to a correspondingly higher value, to imitate worsening fundamentals before the crisis. Qualitatively, results are the same with any $\bar{\theta} = \tilde{\theta}^A < 1$. For $\bar{\theta} = \tilde{\theta}^A > 1$, they are reversed — lower α leads to overestimation of the probability of default.



Note: $\gamma = 2$, $\beta = \gamma + \alpha$, $R = 1.07$, $\tilde{\theta}^A = \bar{\theta} = 0.8$.

Figure 6: Effect of a change in $\bar{\theta}$ with and without the agency.

(provided it is a correct model of the world) might help them achieve this goal.

This extension to our model suggests that rating agencies that do not take into account their effect on the coordination game among investors and have poor information regarding the fundamentals will consistently fail to predict crises. Rating agencies themselves admit that their ability to rate sovereign debt is not as strong as their ability to rate corporations:

> ..It is important, though, that investors realize the limitations of this exercise [assigning sovereign ratings], which is necessarily far less certain than our ability to analyze either bank or corporate risks of default. Fitch (1998).

Our model suggests that this difference in accuracy might be one reason that rating agencies have not been found to downgrade sovereign debt ratings prior to crises but frequently downgrade private companies before financial troubles surface.

5 Conclusion

We use a global game model of sovereign debt roll–over to analyze the effects of introducing a rating agency to financial markets. The model helps explain a number of observations in recent empirical literature on the impact and behavior of sovereign credit ratings. We also find that if a coordination game is a proper description of investors' behavior, there are a number of costs associated with introduction of a rating agency, including an increase in the volatility of financial markets. These costs are mainly due to the fact that investors put less weight on their private signals when credit ratings are available. The model also highlights the importance of supplying high quality information directly to investors.

While the model is formulated with sovereign debt in mind, it can be directly applied to corporate debt roll–over with a rating agency. The difference will be in the interpretation of "fundamentals" and the precision of information.

It is important to emphasize that this paper is by no means a complete cost–benefit analysis of the role rating agencies play in financial markets. We merely point out some potential costs that can arise from introducing a rating agency in a coordination game by heterogeneous investors. One should not conclude on the basis of the paper that rating agencies are harmful, as this paper does not address the benefits that arise from the provision of public information that might be costly to collect. We attempt such analysis in a related project, still in progress.

The model can also serve as a stepping stone for many other potentially instructive extensions. Although the model is formulated in terms of investors' decisions on whether to roll over the debt, it can be reformulated in terms of the investment decision. This change would allow for richer dynamics that would endogenize the cost of debt or risk–premium, the size of the debt stock, and potentially even the cost of default.

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Appendix. Proofs and Solutions

Proof of Proposition 2

Taking implicitly the derivative of (4) with respect to β, obtain

$$\frac{\partial\theta^*}{\partial\beta} = -\frac{\phi\gamma\ \left((\theta^* - \bar{\theta})\sqrt{\gamma+\beta} + \rho\right)}{2\,\beta\,\sqrt{\beta}\,\sqrt{\gamma+\beta}(\sqrt{\beta} - \gamma\phi)},$$

where ϕ is standard normal density function. As $\phi \in (0; 1/\sqrt{2\pi})$ and uniqueness requires that $\sqrt{\beta}/\gamma \geq \frac{1}{\sqrt{2\pi}}$, the denominator is positive and the derivative then is negative if and only if

$$(\theta^* - \bar{\theta})\sqrt{\gamma+\beta} + \rho > 0 \ \text{ or } \ \theta^* > \bar{\theta} - \frac{\rho}{\sqrt{\gamma+\beta}}.$$

However, θ^* is endogenous. We know that $\partial\theta^*/\partial\beta = 0$ if and only if $\theta^* = \bar{\theta} - \rho/\sqrt{\gamma+\beta}$. We can substitute this expression back into (4) to obtain

$$\bar{\theta} = \frac{\rho}{\sqrt{\gamma+\beta}} + \Phi\left(\sqrt{\frac{\beta}{\gamma+\beta}}\rho\right) \equiv T.$$

We know from Proposition 1 that $\partial\theta^*/\partial\bar{\theta} < 0$. Therefore we know that $\partial\theta^*/\partial\beta < 0$ if and only if $\bar{\theta} < T$, which gives us a necessary and sufficient conditions. Stricter sufficient conditions follow immediately. ■

Proof of Proposition 5

Using equations (4) and (7) we can see that $\theta^* > \theta^{A*}$ if and only if

$$\theta^* - \bar{\theta} + \sqrt{\gamma+\beta}\,\rho > (\gamma+\alpha)\theta^{A*} - \gamma\bar{\theta} - \alpha\tilde{\theta}^A + \sqrt{\gamma+\alpha+\beta}\,\rho.$$

The equality $\theta^* = \theta^{A*}$ holds if

$$\tilde{\theta}^A = \theta^* + \frac{\sqrt{\gamma+\alpha+\beta} - \sqrt{\gamma+\beta}}{\alpha}\,\rho \equiv TI.$$

By Propositions 1 and 4, θ^* does not depend on $\tilde{\theta}^A$ while θ^{A*} is decreasing in $\tilde{\theta}^A$, therefore $\theta^* > \theta^{A*}$ if and only if $\tilde{\theta}^A > TI$. ■

Proof of Proposition 6

$$\frac{\partial D^*}{\partial\bar{\theta}} = -\frac{\partial\theta^*}{\partial\bar{\theta}} = \frac{\gamma\phi\left(\frac{1}{\sqrt{\beta}}\ (\gamma(\theta^* - \bar{\theta}) + \sqrt{\gamma+\beta}\ \rho)\right)}{\sqrt{\beta} - \gamma\phi\left(\frac{1}{\sqrt{\beta}}\ (\gamma(\theta^* - \bar{\theta}) + \sqrt{\gamma+\beta}\ \rho)\right)},$$

$$\frac{\partial D^{A*}}{\partial \bar{\theta}} = -\frac{\partial \theta^{A*}}{\partial \bar{\theta}} = \frac{(\gamma+\alpha)\phi\left(\frac{1}{\sqrt{\beta}}\ \left((\gamma+\alpha)\theta^{A*} - \gamma\,\bar{\theta} - \alpha\,\tilde{\theta}^{A} + \sqrt{\gamma+\alpha+\beta}\ \rho\right)\right)}{\sqrt{\beta} - (\gamma+\alpha)\,\phi\left(\frac{1}{\sqrt{\beta}}\ \left((\gamma+\alpha)\theta^{A*} - \gamma\,\bar{\theta} - \alpha\,\tilde{\theta}^{A} + \sqrt{\gamma+\alpha+\beta}\ \rho\right)\right)}.$$

At a point where $\theta^* = \theta^{A*}$,

$$\Phi\left(\frac{1}{\sqrt{\beta}}\ (\gamma(\theta^* - \bar{\theta}) + \sqrt{\gamma+\beta}\ \rho)\right) = \Phi\left(\frac{1}{\sqrt{\beta}}\ \left((\gamma+\alpha)\theta^{A*} - \gamma\,\bar{\theta} - \alpha\,\tilde{\theta}^{A} + \sqrt{\gamma+\alpha+\beta}\ \rho\right)\right),$$

and therefore

$$\phi\left(\frac{1}{\sqrt{\beta}}\ (\gamma(\theta^* - \bar{\theta}) + \sqrt{\gamma+\beta}\ \rho)\right) = \phi\left(\frac{1}{\sqrt{\beta}}\ \left((\gamma+\alpha)\theta^{A*} - \gamma\,\bar{\theta} - \alpha\,\tilde{\theta}^{A} + \sqrt{\gamma+\alpha+\beta}\ \rho\right)\right) \equiv \phi(⋇).$$

Thus,

$$\partial D^{A*}/\partial\bar{\theta} - \partial D^{*}/\partial\bar{\theta} = \frac{(\gamma+\alpha)\phi(⋇)}{\sqrt{\beta} - (\gamma+\alpha)\,\phi(⋇)} - \frac{\gamma\phi(⋇)}{\sqrt{\beta} - \gamma\phi(⋇)} = \frac{\alpha\sqrt{\beta}\phi(⋇)}{(\sqrt{\beta} - (\gamma+\alpha)\,\phi(⋇))(\sqrt{\beta} - \gamma\phi(⋇))} > 0,$$

since $\alpha, \beta, \phi(⋇) > 0$, and, as we established above, each component of the denominator is positive when uniqueness conditions are satisfied. ■

Proof of Proposition 7

Taking implicitly the derivative of (7) with respect to β, obtain

$$\frac{\partial \theta^{A*}}{\partial \beta} = -\frac{\phi(\gamma+\alpha)\ \left(\sqrt{\gamma+\alpha+\beta}(\theta^{A*} - \theta^{A})\ + \rho\right)}{2\,\beta\,\sqrt{\beta}\,\sqrt{\gamma+\alpha+\beta}(\sqrt{\beta} - (\gamma+\alpha)\phi)}.$$

As $\phi \in (0; 1/\sqrt{2\pi})$ and now $\sqrt{\beta}/(\gamma+\alpha) \geq \frac{1}{\sqrt{2\pi}}$, the denominator is positive and the derivative then is negative if and only if

$$(\theta^{A*} - \theta^{A})\,\sqrt{\gamma+\alpha+\beta} + \rho > 0 \quad \text{or} \quad \theta^{A*} > \theta^{A} - \frac{\rho}{\sqrt{\gamma+\alpha+\beta}}.$$

We know that $\partial\theta^{A*}/\partial\beta = 0$ if and only if $\theta^{A*} = \theta^{A} - \rho/\sqrt{\gamma+\alpha+\beta}$. We can substitute this expression back into (6) to obtain

$$\theta^{A} = \frac{\rho}{\sqrt{\gamma+\alpha+\beta}} + \Phi\left(\sqrt{\frac{\beta}{\gamma+\alpha+\beta}}\rho\right) \equiv TA.$$

We know from Proposition 4 that $\partial\theta^{A*}/\partial\bar{\theta} < 0$. Therefore we know that $\partial\theta^{A*}/\partial\beta < 0$ if and only if $\theta^{A} < TA$, which gives us a necessary and sufficient conditions. Stricter sufficient conditions follow immediately.

Taking implicitly the derivative of (7) with respect to α, obtain

$$\frac{\partial \theta^{A*}}{\partial \alpha} = \frac{\phi(\theta^{A*} - \tilde{\theta}^{A} - \frac{\rho}{2\sqrt{\gamma+\alpha+\beta}})}{\sqrt{\beta} - (\gamma+\alpha)\phi}$$

As $\phi \in (0; 1/\sqrt{2\pi})$ and $\sqrt{\beta}/(\gamma+\alpha) \geq \frac{1}{\sqrt{2\pi}}$, the denominator is positive and the derivative is negative if and only if

$$\theta^{A*} < \tilde{\theta}^A + \frac{\rho}{2\sqrt{\gamma+\alpha+\beta}}.$$

The derivative is equal to zero if $\theta^{A*} < \tilde{\theta}^A + \frac{\rho}{2\sqrt{\gamma+\alpha+\beta}}$. We can substitute this back into (6), however, in general we would not be able to find a closed form condition on $\tilde{\theta}^A$. The expression simplifies, however, if we assume $\tilde{\theta}^A = \bar{\theta}$ and therefore $\tilde{\theta}^A = \bar{\theta} = \theta^A$. Since both ε and ν are mean zero, this will be true on average, as $\bar{\theta}$ is unconditional mean of $\tilde{\theta}^A$. In this case we can obtain the condition

$$\tilde{\theta}^A = \bar{\theta} = \theta^A = -\frac{\rho}{2\sqrt{1+\alpha+\beta}} + \Phi\left(\frac{\gamma+\alpha+2\beta}{2\sqrt{\beta}\sqrt{\gamma+\alpha+\beta}}\,\rho\right) \equiv TAa$$

Once again, since $\partial\theta^{A*}/\partial\theta^A < 0$, $\partial\theta^{A*}/\partial\alpha < 0$ if and only if $\tilde{\theta}^A = \bar{\theta} = \theta^A > 0$. ■

Institute for International Integration Studies
The Sutherland Centre, Trinity College Dublin, Dublin 2, Ireland