Large deviations for equilibrium measures and selection of subaction

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Abstract

Given a Lipschitz function \( f : \{1, ..., d\}^N \to \mathbb{R} \), for each \( \beta > 0 \) we denote by \( \mu_\beta \) the equilibrium measure of \( \beta f \) and by \( h_\beta \) the main eigenfunction of the Ruelle Operator \( L_\beta f \). Assuming that \( \{\mu_\beta\}_{\beta > 0} \) satisfy a large deviation principle, we prove the existence of the uniform limit \( V = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(h_\beta) \). Furthermore, the expression of the deviation function is determined by its values at the points of the union of the supports of maximizing measures.

We study a class of potentials having two ergodic maximizing measures and prove that a L.D.P. is satisfied. The deviation function is explicitly exhibited and does not coincide with the one that appears in the paper by Baraviera-Lopes-Thieullen which considers the case of potentials having a unique maximizing measure.

1 Introduction

We denote by \( X \) the Bernoulli space \( \{1, ..., d\}^N, N = \{1, 2, 3, ...\} \), and by \( \sigma \) the shift map acting on \( X \). The metric considered satisfies \( d_\theta(x, y) = \theta \min\{i, x_i \neq y_i\} \), where \( x = (x_1x_2x_3...) \), \( y = (y_1y_2y_3...) \) and \( \theta \in (0, 1) \) is fixed. If \( x_1, ..., x_n \in \{1, ..., d\} \) and \( y = (y_1y_2y_3...) \in X \), the notation \((x_1...x_ny) \in X \) represents the element \((x_1x_2...x_ny_1y_2y_3...) \in X \). A cylinder is a subset of \( X \) of the form \([x_1...x_n] := \{(x_1...x_ny) \mid y \in X \} \). We denote by \( C(X) \) the set of continuous functions from \( X \) to \( \mathbb{R} \) and by \( P(X) \) the set of probabilities on \( X \).
Let $f : X \to \mathbb{R}$ be a Lipschitz function and, for each $\beta > 0$, denote by $L_{\beta f}$ the Ruelle operator associated with $\beta f$, which is defined by

$$L_{\beta f} : C(X) \to C(X), \quad (L_{\beta f}(w))(x) = \sum_{a \in \{1, \ldots, d\}} e^{\beta f(ax)} w(ax).$$

We denote by $\nu_{\beta}$ the eigenmeasure of $L_{\beta f}$, that is, the probability satisfying

$$\int L_{\beta f}(u) \, d\nu_{\beta} = e^{P(\beta f)} \int u \, d\nu_{\beta}$$

for any continuous function $u : X \to \mathbb{R}$, and by $h_{\beta}$ the main eigenfunction of $L_{\beta f}$. More precisely, $h_{\beta}$ is Lipschitz, $L_{\beta f}(h_{\beta}) = e^{P(\beta f)} h_{\beta}$ and $\int h_{\beta} \, d\nu_{\beta} = 1$. Let $g_{\beta} = \beta f + \log(h_{\beta}) - \log(h_{\beta} \circ \sigma) - P(\beta f)$. The functions $g_{\beta}$ and $\beta f - P(\beta f)$ are cohomologous and $L_{g_{\beta}} 1 = 1$. The eigenmeasure $\mu_{\beta}$ of $L_{g_{\beta}}$ is $\sigma$-invariant and coincides with the equilibrium measure of $\beta f$, that is,

$$\int f \, d\mu_{\beta} + h(\mu_{\beta}) = P(\beta f) = \sup_{\{\mu \in P(X); \mu \text{ is } \sigma \text{-invariant}\}} \int f \, d\mu + h(\mu).$$

Furthermore $d\mu_{\beta} = h_{\beta} \, d\nu_{\beta}$. Classical results on thermodynamic formalism can be found in [6] and [20].

At the zero temperature case, in thermodynamic formalism, the above objects are studied for large $\beta$. In this case some intersections with ergodic optimization appear ([1], [9], [10], [13]). It is well known, for instance, that

$$\lim_{\beta \to +\infty} \frac{P(\beta f)}{\beta} = m(f),$$

where

$$m(f) := \sup_{\{\mu \in P(X); \mu \text{ is } \sigma \text{-invariant}\}} \int f \, d\mu. \quad (1)$$

Any possible limit (weak* topology) of a subsequence of $(\mu_{\beta})_{\beta > 0}$ attains the supremum in (1) being called a maximizing measure of $f$. Furthermore, $(\frac{1}{\beta} \log(h_{\beta}))_{\beta > 0}$ is an equicontinuous family and any possible uniform limit $V$ of a subsequence of $(\frac{1}{\beta} \log(h_{\beta}))$ is a calibrated subaction [9], that is, it satisfies, for any $x \in X$, the equation

$$\sup_{\sigma(y)=x} \left[ f(y) + V(y) - V(x) - m(f) \right] = 0.$$

The limit function $V$ is Lipschitz and $R_- := f + V - V \circ \sigma - m(f)$ is the uniform limit of the corresponding subsequence of $\frac{\mu_{\beta}}{\beta}$, which satisfies:

1) $R_-$ is Lipschitz and $R_- \leq 0$,

2) $R_-$ and $f - m(f)$ are cohomologous,

3) For any $x \in X$ there exists $y \in \sigma^{-1}(x)$ satisfying $R_-(y) = 0$.

Define $R_+ := -R_-$, $R_+^n(x) := \sum_{j=0}^{n-1} R_+(\sigma^j(x))$ and $R_+^\infty(x) := \lim_{n \to +\infty} R_+^n(x)$ ($R_+^\infty$ can assume the value $+\infty$).
Subactions and maximizing measures are dual objects linked in a particular form when we study the speed of convergence of \( \mu_\beta \) to a maximizing measure. From [3] is known that, when the maximizing measure of \( f \) is unique, there exists the uniform limit \( R_\ast \) of \( \int g_\beta \), \( (\beta \to +\infty) \). Furthermore, the measures \( (\mu_\beta)_{\beta>0} \) satisfy a Large Deviation Principle (L.D.P.), in the following sense, also used in the present work: there exists a lower semicontinuous function \( I : \mathbb{X} \to [0, +\infty] \) satisfying, for any cylinder \( k \subset \mathbb{X} \),

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta(k)) = -\inf_{x \in k} I(x).
\]

The deviation function \( I \) in [3] is given by \( I = R^\infty_\ast \). It can assume the value \( +\infty \).

In [18, 19] this result has been generalized. Given \( x \in \mathbb{X} \), \( n \in \mathbb{N} \) and \( \beta > 0 \), consider the probability \( m_{x,\beta,n} \in P(\mathbb{X}) \) defined by \( \int w \, dm_{x,\beta,n} = L_{g_\beta}^n(w)(x) \). If the maximizing measure of \( f \) is unique, then\(^1\)

\[
\lim_{n,\beta \to +\infty} \frac{1}{\beta} \log(m_{x,\beta,n}(k)) = \lim_{n,\beta \to +\infty} \frac{1}{\beta} \log(L^n_{g_\beta}(\chi_k)(x)) = -\inf_{z \in k} R^\infty_\ast(z) \tag{2}
\]

for any cylinder \( k \subset \mathbb{X} \). Given a continuous function \( w \), \( L^n_{g_\beta}(w) \) converges uniformly to \( \int w \, d\mu_\beta \) \( (n \to +\infty) \). Therefore, for any \( x \in \mathbb{X} \), the probabilities \( m_{x,\beta,n} \) converge to \( \mu_\beta \) in the weak* topology \( (n \to +\infty) \). Consequently, from (2), for any \( x \in \mathbb{X} \),

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta(k)) = \lim_{\beta \to +\infty} \lim_{n \to +\infty} \frac{1}{\beta} \log(m_{x,\beta,n}(k)) = -\inf_{z \in k} R^\infty_\ast(z).
\]

In [5] the main result of [3], stated above, was proved for a more general class of functions (satisfying the Walters condition) on a countable mixing subshift with the BIP property. However, in both works it was assumed the existence of a unique maximizing measure to \( f \).

If we do not assume the hypothesis of unicity, then there are some natural questions to be considered:

**question 1:** there exists \( V := \lim_{\beta \to +\infty} \frac{1}{\beta} \log(h_\beta) \)?

**question 2:** there exists \( \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta(k)) \) for any cylinder \( k \)?

**question 3:** there are relations between \( V \) and the deviation function \( I \)?

Initially, it is natural to assume that the answer to the question 3 can be obtained generalizing the results in [3]. In the case of existing the uniform

\(^1\) we write \( \lim_{a_\beta,n \to +\infty} a_\beta,n = a \) if for any \( \epsilon > 0 \) there exists \( L > 0 \) such that \( n, \beta > L \Rightarrow |a_\beta,n - a| < \epsilon \).
limit $R_+ = \lim_{\beta \to +\infty} -g(\beta)\beta$, we could try to prove that $\mu_\beta$ satisfies a L.D.P. with deviation function $I = R_+^\infty$. However, in [2] it is proved that this assertion is false. Even in the case there exist the limits in questions 1 and 2, one can get an explicit example where $I \neq R_+^\infty$.

We will show that, when the assertion in question 2 is satisfied, an affirmative answer to the question 1 exists. In this case, we also present an answer to the question 3, determining relations between $R_+$ and $I$.

Several results are known concerning the problem of selection of a maximizing measure [2, 4, 7, 8, 11, 14, 15, 16]. In this work we present an improvement in the study of selection of the subaction as a consequence of our results on large deviations on the first part of the paper.

Define

$$M_{\text{max}}(f) := \{\mu \in P(X) : \mu \text{ is } \sigma \text{ - invariant and } \int f \, d\mu = m(f)\}$$

and

$$X_{\text{max}}(f) := \bigcup_{\mu \in M_{\text{max}}(f)} \text{supp}(\mu).$$

$X_{\text{max}}(f)$ is called the Mather set of $f$. It is a subset of the Aubri set

$$\Omega(f) = \left\{ x \in X | \lim_{\varepsilon \to 0^+} \sup_{n \geq 1} \sup_{d(x,z) < \varepsilon} \left[ \left( f(z) + \ldots + f(\sigma^{n-1}z) - n \cdot m(f) \right) - \beta \right] = 0 \right\}. $$

Furthermore, $\text{supp}(\mu) \subset X_{\text{max}}(f)$ iff $\text{supp}(\mu) \subset \Omega(f)$ iff $\mu$ is a maximizing measure of $f$ [9].

In the section 2. we will prove the following theorem:

**Theorem 1.** With the above notations, suppose that for any cylinder $k \subset X$, there exists

$$\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta(k)).$$

Then, denoting $x = (x_1x_2x_3\ldots)$,

1. The family of probabilities $(\mu_\beta)_{\beta > 0}$ satisfies a L.D.P. with deviation function $I : X \to [0, +\infty]$,

$$I(x) := -\lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([x_1\ldots x_n])). \quad \text{(3)}$$

2. There exists the uniform limit $R_+ := -\lim_{\beta \to +\infty} \frac{g(\beta)}{\beta}$. It satisfies

$$I = R_+ + I \circ \sigma \quad \text{and} \quad I \geq R_+^\infty.$$
3. 

\[
I(x) = \inf_{y \in X_{\max}(f)} \liminf_{n \to +\infty} \left( R^\alpha_n(x_1 \ldots x_n y) + I(y) \right).
\]

If \( R^\infty_+(x) < +\infty \), there exists at least one point \( y \in X_{\max}(f) \) which is an accumulation point of \( \{\sigma^n x\}_{n=1,2,\ldots} \). For any such \( y \)

\[
I(x) = R^\infty_+(x) + I(y).
\]

4. There exists the uniform limit 

\[
V = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(h_\beta).
\]

5. The eigenmeasures \( \nu_\beta \) satisfy a L.D.P. with deviation function \( I + V \).

Some remarks:

1. In the equation (3) we do not exclude the possibility \( I(x) = +\infty \). When we write \( I(x) = R^\infty_+(x) + I(\sigma x) \) we may have \( +\infty = R^\infty_+(x) + \infty \).

Following the above discussion, the function \( R^\infty_+ \) is real-valued, nonnegative, Lipschitz and for any \( x \in X \), 

\[
\min_{a \in \{1, \ldots, d\}} R^\infty_+(ax) = 0.
\]

2. Under the hypothesis of the theorem we get:

2.1. There exists at least one point \( \tilde{y} \in X_{\max}(f) \) satisfying 

\[
I(\tilde{y}) = 0.
\]

Indeed, let \( \mu_\infty \) be a probability on \( X \) such that, for an increasing sequence \( \beta_i \to +\infty \), \( \mu_{\beta_i} \to \mu_\infty \) (weak* topology). Let \( \tilde{y} \in \text{supp}(\mu_\infty) \), that is, \( \mu_\infty([y_1 \ldots y_n]) > 0 \) for any cylinder \([y_1 \ldots y_n] \) containing \( \tilde{y} \). In this way, from the hypothesis of the theorem, 

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([y_1 \ldots y_n])) = \lim_{\beta_i \to +\infty} \frac{1}{\beta_i} \log(\mu_{\beta_i}([y_1 \ldots y_n])) = 0,
\]

because \( \mu_{\beta_i}([y_1 \ldots y_n]) \to \mu_\infty([y_1 \ldots y_n]) > 0 \). It follows from item 1. of the theorem that \( I(\tilde{y}) = 0 \).

2.2. If \( R^\infty_+(x) < +\infty \) then \( I(x) < +\infty \). Consequently, as \( R^\infty_+(x) = 0 \) for any \( x \in X_{\max}(f) \), we conclude that \( I(x) < +\infty \) for any \( x \in X_{\max}(f) \).

Indeed, in the proof of the Theorem 4 we will show that (see eq. (10) below)

\[
I(x) \leq \liminf_{n \to +\infty} R^\alpha_n(x_1 \ldots x_n y) + I(y) \quad \forall y \in X.
\]

As \( I(\tilde{y}) = 0 \) at some point \( \tilde{y} \in X_{\max}(f) \) and \( R_+ \) is Lipschitz, there exists a constant \( c > 0 \) satisfying

\[
I(x) \leq \liminf_{n \to +\infty} R^\alpha_n(x_1 \ldots x_n \tilde{y}) \leq \liminf_{n \to +\infty} R^\alpha_n(x) + c(\theta + \ldots + \theta^n) \leq R^\infty_+(x) + \frac{c\theta}{1 - \theta}.
\]
2.3. In the equation \((4)\), if \(R^\infty_\beta(x) = +\infty\) then, following computations as above, we get
\[
\lim \inf_{n \to +\infty} \left( R^\infty_\beta(x_1...x_ny) + I(y) \right) = +\infty \quad \forall y \in X_{\max}(f).
\]
In this case we write
\[
\inf_{y \in X_{\max}(f)} \lim \inf_{n \to +\infty} \left( R^\infty_\beta(x_1...x_ny) + I(y) \right) = +\infty.
\]
If \(R^\infty_\beta(x) < +\infty\) then
\[
\lim \inf_{n \to +\infty} \left( R^\infty_\beta(x_1...x_ny) + I(y) \right) < +\infty \quad \forall y \in X_{\max}(f).
\]

2.4. If \(I(y) = 0\) for all \(y \in X_{\max}(f)\) then \(I(x) = R^\infty_\beta(x)\) for all \(x \in X\) (it follows from item 3. of the theorem). This is the case, for instance, if the maximizing measure of \(f\) is unique.

2.5. The equation \((4)\) remains valid if we replace \(y \in X_{\max}(f)\) by \(y \in X\). It follows a similar argument with \(\inf_{y \in X_{\max}(f)}\) replaced by \(\inf_{y \in X}\) in the proof.

3. There exist constants \(C_1, C_2 > 0\) satisfying, for any \(x, y \in X, n \geq 1\), and \(\beta\) sufficiently large,
\[
-\beta C_1 < \log(h_\beta(x)) < \beta C_1, \quad |\log(h_\beta(x)) - \log(h_\beta(y))| < \beta C_1 d_\theta(x, y) \quad (5)
\]
and
\[
e^{-\beta n C_2} < \mu_\beta([x_1...x_n]) < e^{\beta n C_2}. \quad (6)
\]

For a proof of \((5)\), see \[9\] p. 1404 or \[19\] Lemma 28. For a proof of \((6)\), see \[20\], proof of the corollary 3.2.1., observing that \(\mu_\beta\) is the equilibrium measure of \(\beta f + \log(h_\beta) - \log(h_\beta \circ \sigma) - P(\beta f)\), and use \((5)\).

If the hypothesis of the theorem is not satisfied, from \((6)\), applying a Cantor’s diagonal argument, we obtain the existence of a sequence \(\beta_j\) for which all limits \(\lim_{\beta_j \to +\infty} \frac{1}{\beta_j} \log(\mu_\beta_j(k))\) exist. A similar result is valid for this subsequence, with all \(\beta\) replaced by \(\beta_j\) in the statement of the theorem.

4. If \(X\) is a subshift of finite type defined from an aperiodic matrix, the theorem remains valid except by the equation \((4)\) which must be replaced by the following equation
\[
I(x) = \inf_{y \in X_{\max}(f)} \left[ \lim \inf_{\epsilon \to 0^+} \inf_{n \geq 1} \inf_{d(x, z) < \epsilon} R^n_\beta(z) + I(y) \right]. \quad (7)
\]
We will prove the equation (7) after the proof of the Theorem 1.

In the section 3. we will apply the above theorem studying the L.D.P. for the equilibrium measures of a class of Lipschitz functions $f : \{0, 1\}^\mathbb{N} \to \mathbb{R}$ satisfying\(^2\)

$$f|_{[0]} = b, \ f|_{[1]} = d, \ f(0^\infty) = f(1^\infty) = 0, \ f|_{[0^\infty]} = a_n, \ f|_{[1^n]} = c_n, \ n \geq 2$$

where $b, d, a_n, c_n < 0$. The deviation function $I$ is presented and, in the case $\sum_{j \geq 2} a_j < b + d + \sum_{j \geq 2} c_j$, this function differs from the one that appears in [3] (see also [2]).

2 Proof of Theorem 1

The following general result is very helpful and proves item 1. of Theorem 1.

**Lemma 2.** Let $\eta_\beta$ be a sequence of probabilities on $X$. Suppose that for any cylinder $k \subset X$ there exists the limit $\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_\beta(k))$. Then, denoting $x = (x_1x_2x_3...)$,

1. The function $I : X \to [0, +\infty]$,

$$I(x) := - \lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_\beta([x_1...x_n]))$$

is lower semi-continuous.

2. For any cylinder $k \subset X$,

$$\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_\beta(k)) = - \inf_{x \in k} I(x).$$

**Remark:** In [5] this result is generalized for Gibbs measures when considering a countable mixing subshift with the BIP property.

**Proof.** The function $I$ is well defined because $\psi_x(n) := \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_\beta([x_1...x_n]))$ exists and it is not increasing with $n$. The function $I : X \to [0, +\infty]$,

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\(^2\)we use the following notations

$0^2 = 00, \ 0^3 = 000, ..., \ 0^\infty = (0000...), \ 1^2 = 11, \ 1^3 = 111, ..., \ 1^\infty = (1111...)$. 

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\( I(x) = \lim_{n \to +\infty} \psi_x(n) \) assume the value \(+\infty\) if \( \lim_{n \to +\infty} \psi_x(n) = -\infty \). Furthermore, denoting \( z^n = (z^n_1, z^n_2, z^n_3, \ldots) \in X \),

\[
I(x) = \lim inf \left[ \lim_{n \to +\infty} \inf_{z \in [x_1, \ldots, x_n]} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_n])) \right] \\
= \lim inf \left[ \lim_{n \to +\infty} \inf_{z \in [x_1, \ldots, x_n]} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_n])) \right] \\
\leq \lim inf \left[ \lim_{m \to +\infty} \inf_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([z^n_1, \ldots, z^n_m])) \right] \\
= \lim inf \left[ \inf_{z \in [x_1, \ldots, x_n]} I(z^n) \right] \\
\]

therefore \( I \) is lower semi-continuous.

Given a cylinder \( k = [x_1, \ldots, x_n] \), for any \( z = (z_1, z_2, z_3, \ldots) \in k \) we have

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}(k)) \geq \lim_{m \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([z_1, \ldots, z_m])) = -I(z). \\
\]

Thus, we get

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}(k)) \geq \sup_{z \in k} -I(z) = -\inf_{z \in k} I(z). \\
\]

On the other hand, as

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_n])) = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\sum_{j=1}^{d} \eta_{\beta}([x_1, \ldots, x_nj])) = \max_{j \in \{1, \ldots, d\}} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_nj])), \\
\]

there exists \( y = (y_1, y_2, y_3, \ldots) \in X \) satisfying

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_n])) = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_ny_1])) = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}([x_1, \ldots, x_ny_1y_2])) = \ldots. \\
\]

Therefore, we finally get

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\eta_{\beta}(k)) = -I(x_1, \ldots, x_ny) \leq \sup_{z \in k} -I(z) = -\inf_{z \in k} I(z). \\
\]

\( \square \)
Lemma 3. Under the hypotheses of the Theorem 1, the deviation function $I$ in (3) satisfies $I(x) \geq I(\sigma(x)) \ \forall x \in X$. Particularly, the function

$$I_0 : X \to [0, +\infty], \ I_0(x) := \lim_{n \to +\infty} I(\sigma^n(x))$$

is constant on each orbit $\Omega_x = \{\sigma^n(x) | n \in \{0, 1, 2, 3, \ldots\}\}, \ x \in X$.

Proof. Denoting $x = (x_1 x_2 x_3 \ldots)$, as $\mu_\beta$ is $\sigma$–invariant, for $n \geq 2$,

$$\frac{1}{\beta} \log(\mu_\beta([x_1 \ldots x_n])) \leq \frac{1}{\beta} \log(\sum_{j=1}^{d} \mu_\beta([jx_2 \ldots x_n])) = \frac{1}{\beta} \log(\mu_\beta([x_2 \ldots x_n])).$$

Then

$$I(x) = -\lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([x_1 \ldots x_n]))$$

$$\geq -\lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([x_2 \ldots x_n])) = I(\sigma(x)).$$

We write $y \in \omega(x), \ x, y \in X$, if there exists an increasing sequence $n_i \to +\infty$ such that $\sigma^{n_i}(x) \to y$.

Corollary 4. Under the hypotheses of Theorem 1, let $I$ be the deviation function defined in (3) and $I_0$ be the function defined in (8).

1. If $y \in \omega(x)$, then $I(y) \leq I_0(x) \leq I(x)$,
2. $I$ is constant on each periodic orbit,
3. If $x \in \omega(y)$ and $y \in \omega(x)$, then $I_0(x) = I(x) = I(y) = I_0(y)$.

Proof. In order to prove 1. we suppose $\sigma^{n_i}(x) \to y$. From the above lemma and using the lower semi-continuity of $I$ we get

$$I(x) \geq I_0(x) = \lim_{n_i \to +\infty} I(\sigma^{n_i}(x)) \geq I(y).$$

The proof of 2. consists in observing that for a periodic orbit $\{x, \ldots, \sigma^n(x)\}$ we have:

$$I(x) \geq I(\sigma(x)) \geq \ldots \geq I(\sigma^n(x)) \geq I(x).$$

Analogously, to prove 3. we observe that from 1. we have

$$I(x) \geq I_0(x) \geq I(y) \geq I_0(y) \geq I(x).$$
Proof of Theorem 1:

proof of 1.
It is a consequence of Lemma 2

proof of 2.
The existence of the limit $R_-$ is a consequence of corollary 48 in [19]. Furthermore, following the Proposition 47 in [19], for $x = (x_0 x_1 x_2 \ldots)$, we get

$$R_+(x) = \lim_{\beta, n \to +\infty} \frac{1}{\beta} \log \frac{\mu_\beta[x_1 \ldots x_n]}{\mu_\beta[x_0 \ldots x_n]}$$

$$= \lim_{n \to +\infty} \left( \lim_{\beta \to +\infty} \frac{1}{\beta} \log \mu_\beta[x_1 \ldots x_n] - \lim_{\beta \to +\infty} \frac{1}{\beta} \log \mu_\beta[x_0 \ldots x_n] \right).$$

Therefore, using Lemma 2 we have

$$I(x) = R_+(x) + I(\sigma(x)).$$

It follows that for each $n$,

$$I(x) = R^n_+(x) + I(\sigma^n(x)), \quad (9)$$

and, taking $n \to +\infty$,

$$I(x) = R^\infty_+(x) + I_0(x)$$

(see also [5]).

proof of 3.
Denoting $x = (x_1 x_2 x_3 \ldots)$, we want to show that

$$I(x) = \inf_{y \in X_{\max}(f)} \lim_{n \to +\infty} \left( R^n_+(x_1 \ldots x_n y) + I(y) \right).$$

For a fixed $y \in X$ we have from (9) that

$$I(x_1 \ldots x_n y) = R^n_+(x_1 \ldots x_n y) + I(y).$$

As $I$ is lower semi-continuous,

$$I(x) \leq \lim_{n \to +\infty} \left( R^n_+(x_1 \ldots x_n y) + I(y) \right). \quad (10)$$

Then, (considering an infimum on the right side)

$$I(x) \leq \inf_{y \in X_{\max}(f)} \lim_{n \to +\infty} \left( R^n_+(x_1 \ldots x_n y) + I(y) \right).$$
Now, we will prove the reverse inequality. If \( R_+^\infty(x) = +\infty \), then \( I(x) = R_+^\infty(x) + I_0(x) = +\infty \) and, as \( R_+ \) is a Lipschitz function, for any \( y \in X_{\text{max}}(f) \),
\[
\liminf_{n \to +\infty} R_+^n(x_1 \ldots x_n y) = +\infty.
\]
So the main equality (4) holds.

If \( R_+^\infty(x) < +\infty \), there exists at least one point \( y \in X_{\text{max}}(f) \) such that is an accumulation point of the sequence \( \{\sigma^n(x)\}_{n=0,1,...} \) (see [17] or Lemma 42 and Cor. 43 in [19] or [5]). We write \( y = (y_1y_2y_3\ldots) \).

It follows that for each \( j \in \mathbb{N} \) there exists some \( m_j > j \) such that
\[
x = (x_1 \ldots x_{m_j} y_1 \ldots y_j x_{m_j+j+1}x_{m_j+j+2} \ldots).
\]
Then
\[
I(x) = (R_+^{m_j}(x_1 \ldots x_{m_j} y_1 \ldots y_j x_{m_j+j+1} \ldots) + I(y_1 \ldots y_j x_{m_j+j+1} \ldots).
\]

When \( j \to +\infty \), using the fact that \( I \) is lower semi-continuous and \( R_+ \) is Lipschitz, we get
\[
I(x) \geq \liminf_{j \to +\infty} I(R_+^{m_j}(x_1 \ldots x_{m_j} y_1 \ldots y_j x_{m_j+j+1} \ldots)) + I(y)
\]
\[
= \liminf_{j \to +\infty} I(R_+^{m_j}(x_1 \ldots x_{m_j} y)) + I(y)
\]
\[
\geq \liminf_{n \to +\infty} I(R_+^n(x_1 \ldots x_n y)) + I(y).
\]
Therefore,
\[
I(x) \geq \inf_{y \in X_{\text{max}}(f)} \liminf_{n \to +\infty} (R_+^n(x_1 \ldots x_n y) + I(y)),
\]
proving the reverse inequality. This concludes the proof of (4).

As we see above, if \( R_+^\infty(x) < +\infty \), there exists at least one point \( y \in X_{\text{max}}(f) \) which is an accumulation point of \( \{\sigma^n(x)\}_{n=1,2,...} \). For any such \( y \), from corollary [4] we have
\[
I(x) = R_+^\infty(x) + I_0(x) \geq R_+^\infty(x) + I(y).
\]

On the other hand, following the notations above
\[
I(x) \leq \liminf_{j \to +\infty} I(x_1 \ldots x_{m_j} y)
\]
\[
= \liminf_{j \to +\infty} R_+^{m_j}(x_1 \ldots x_{m_j} y) + I(y) = \lim_{m_j \to +\infty} R_+^{m_j}(x) + I(y) = R_+^\infty(x) + I(y),
\]
where we use that $I$ is lower semi-continuous, $R^n_+(x)$ is increasing with $n$, $x_{m_j+1}...x_{m_j+j} = y_1...y_j$ and that $R_+$ is Lipschitz. This concludes the proof of the equation

$$I(x) = R^\infty_+(x) + I(y).$$

**Proof of 4. and 5.**

We denote by $\nu_\beta$ the eigenmeasure of the Ruelle Operator $L_\beta f$. The probabilities $\nu_\beta$ and $\mu_\beta$ satisfy $h_\beta d\nu_\beta = d\mu_\beta$, that is,

$$\int w \cdot h_\beta d\nu_\beta = \int w d\mu_\beta \quad \forall w \in C(X).$$

Consequently, given a cylinder $k \subset X$, from (5) and (6), there exists a constant $C_k$ such that, for $\beta$ sufficiently large,

$$-\beta C_k < \log(\nu_\beta(k)) < \beta C_k.$$

We suppose initially the existence of the uniform limit

$$V_1 := \lim_{\beta_j \to +\infty} \frac{1}{\beta_j} \log(h_{\beta_j}).$$

For a cylinder $k_0$ and an accumulation point $a$ of $\frac{1}{\beta_j} \log(\nu_{\beta_j}(k_0))$, there exists a subsequence $\beta_{j_i}$ such that

$$\lim_{\beta_{j_i} \to +\infty} \frac{1}{\beta_{j_i}} \log(\nu_{\beta_{j_i}}(k_0)) = a.$$

Using a Cantor’s diagonal argument we can suppose that for any cylinder $k$ there exists the limit of $\frac{1}{\beta_j} \log(\nu_{\beta_j}(k))$. By hypothesis, $\mu_\beta$ satisfies a L.D.P. with deviation function $I$. Fixed any point $z = (x_1x_2x_3...)$, for each $n$,

$$\frac{1}{\beta_{j_i}} \log(\nu_{\beta_{j_i}}([x_1...x_n])) + \inf_{[x_1...x_n]} \frac{1}{\beta_{j_i}} \log(h_{\beta_{j_i}}) \leq \frac{1}{\beta_{j_i}} \log(\mu_{\beta_{j_i}}([x_1...x_n]))$$

$$\leq \frac{1}{\beta_{j_i}} \log(\nu_{\beta_{j_i}}([x_1...x_n])) + \sup_{[x_1...x_n]} \frac{1}{\beta_{j_i}} \log(h_{\beta_{j_i}}).$$

Taking $\beta_{j_i} \to +\infty$, we have

$$\lim_{\beta_{j_i} \to +\infty} \frac{1}{\beta_{j_i}} \log(\nu_{\beta_{j_i}}([x_1...x_n])) + \inf_{[x_1...x_n]} V_1 \leq \lim_{\beta_{j_i} \to +\infty} \frac{1}{\beta_{j_i}} \log(\mu_{\beta_{j_i}}([x_1...x_n]))$$

$$\leq \lim_{\beta_{j_i} \to +\infty} \frac{1}{\beta_{j_i}} \log(\nu_{\beta_{j_i}}([x_1...x_n])) + \sup_{[x_1...x_n]} V_1.$$
When \( n \to +\infty \) (applying Lemma 2) we have

\[
- \lim_{n \to +\infty} \lim_{\beta_j \to +\infty} \frac{1}{\beta_j} \log(\nu_{\beta_j}([x_1...x_n])) = I(z) + V_1(z).
\]

Using Lemma 2 again, we conclude that \( \nu_{\beta_j} \) satisfies a L.D.P. with deviation function \( I + V_1 \). Then

\[
a = - \inf_{x \in k_0} (I(x) + V_1(x)).
\]

As \( a \) is any possible accumulation point of \( \frac{1}{\beta_j} \log(\nu_{\beta_j}(k_0)) \) we conclude that

\[
\lim_{\beta_j \to +\infty} \frac{1}{\beta_j} \log(\nu_{\beta_j}(k_0)) = - \inf_{x \in k_0} (I(x) + V_1(x)).
\]

Now we will prove the existence of the limit function \( V \). Suppose that for subsequences \( \beta_i \) and \( \beta_j \) we have

\[
\lim_{\beta_i \to +\infty} \frac{1}{\beta_i} \log(h_{\beta_i}) = V_1 \quad \text{and} \quad \lim_{\beta_j \to +\infty} \frac{1}{\beta_j} \log(h_{\beta_j}) = V_2.
\]

Applying 2. of the Theorem 1 we obtain \( V_2 - V_2 \circ \sigma = V_1 - V_1 \circ \sigma \). Therefore, \( V_2 = V_1 + C \) for some constant \( C \).

Applying the above conclusions on the L.D.P. for the set \( X \) (the full space) we get

\[
0 = \lim_{\beta_i \to +\infty} \frac{1}{\beta_i} \log(\nu_{\beta_i}(X)) = - \inf_{x \in X} (I(x) + V_1(x))
\]

and

\[
0 = \lim_{\beta_j \to +\infty} \frac{1}{\beta_j} \log(\nu_{\beta_j}(X)) = - \inf_{x \in X} (I(x) + V_2(x)).
\]

Thus, we have

\[
0 = - \inf_{x \in X} (I(x) + V_2(x)) = - \inf_{x \in X} (I(x) + V_1(x) + C)
\]

\[
= - \inf_{x \in X} (I(x) + V_1(x)) + C = 0 + C = C,
\]

proving that \( V_2 = V_1 \). This shows that exists the uniform limit \( V = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(h_{\beta}) \), proving 4.

The previous arguments on the L.D.P. for the measures \( \nu_{\beta_j} \) can be applied to the general family of measures \( \mu_{\beta} \), proving 5. \( \square \)

**Proof of remark 4. and equation (7):** If \( X \) is a subshift of finite type defined from an aperiodic matrix, the arguments used in the above proof
are also valid except by some estimates in the proof of (4). In this case the equation (4) can be replaced by the equation (7), that is,

\[ I(x) = \inf_{y \in X_{\text{max}}(f)} \left[ \liminf_{\epsilon \to 0^+} \inf_{n \geq 1} R^\infty_+(z) + I(y) \right]. \]

Indeed, from (9),

\[ \inf_{d(x,z) < \epsilon} R^\infty_+(z) + I(y) = \inf_{d(x,z) < \epsilon} I(z). \]

As \( I \) is lower semi-continuous, for any \( x, y \in X \), we have

\[ I(x) \leq \left[ \liminf_{\epsilon \to 0^+} \inf_{n \geq 1} I(z) \right], \]

and then

\[ I(x) \leq \inf_{y \in X_{\text{max}}(f)} \left[ \liminf_{\epsilon \to 0^+} \inf_{n \geq 1} R^\infty_+(z) + I(y) \right]. \]

In order to prove the reverse inequality we remark that if \( R^\infty_+(x) = +\infty \), then \( I(x) = R^\infty_+(x) + I_0(x) = +\infty \) and using the above inequality, the equation (7) corresponds to the equality +\( \infty = +\infty \). Suppose \( R^\infty_+(x) < \infty \) and consider \( \eta > 0 \). As \( R_+ \) is Lipschitz, there exists a constant \( C > 0 \) such that

\[ |R_+(a) - R_+(b)| \leq C d(a, b), \quad \forall a, b \in X. \]

Let \( j_0 \) be such that \( \frac{C \theta}{1 - \theta} < \eta \). Take \( y \in X_{\text{max}}(f) \cap \omega(x) \). Then, from corollary (4),

\[ I(x) = R^\infty_+(x) + I_0(x) \geq R^\infty_+(x) + I(y). \]

Given \( \epsilon > 0 \), let \( j > j_0 \) be such that \( \theta^j < \epsilon \). For this \( j \) there exists \( m_j > j \) such that

\[ x = (x_1, \ldots, x_{m_j}, y_1, \ldots, y_j, x_{m_j+j+1}, x_{m_j+j+2}, \ldots). \]

Let \( z_\epsilon = (x_1, \ldots, x_{m_j}, y) \). Then,

\[ I(x) \geq R^\infty_+(x) + I(y) \geq R^\infty_+(x) + I(y) \geq R^\infty_+(x_{m_j}) + I(y) - \eta = R^\infty_+(z_\epsilon) + I(y) - \eta. \]

Therefore, \( d(x, z_\epsilon) < \epsilon \), \( \sigma^m(z_\epsilon) = y \) and \( I(x) \geq (R^\infty_+(z_\epsilon) + I(y)) - \eta \). This construction shows that

\[ I(x) \geq \inf_{y \in X_{\text{max}}(f)} \left[ \liminf_{\epsilon \to 0^+} \inf_{n \geq 1} R^\infty_+(z) + I(y) \right] - \eta. \]

As \( \eta \) can be arbitrarily small, we conclude the proof. □
3 Application for an explicit example

Now we use the results described above in order to complete the study of Large Deviations for the equilibrium measures of a family of functions previously studied in [2].

Definition 5. We write \( f \in W \) if \( f: \{0, 1\}^\mathbb{N} \to \mathbb{R} \) is a Lipschitz function and there exist negative numbers \( b,d, \{c_n\}_{n \geq 2}, \{a_n\}_{n \geq 2}, \) such that, for \( n \geq 2, \)
\[
f|_{[0]} = b, \quad f|_{[1]} = d, \quad f(0^\infty) = f(1^\infty) = 0, \quad f|_{[0]}^1 = a_n, \quad f|_{[1]}^1 = c_n. \tag{11}
\]

Any function \( f \in W \) belongs to the class of potentials defined by P. Walters [21] where \( 0 = a = c, b = b_1 = b_2 = ... \) and \( d = d_1 = d_2 = ... \). We remark that \( \sum_{i \geq 2} a_i > -\infty \) and \( \sum_{i \geq 2} c_i > -\infty \), because \( f \) is Lipschitz and \( f(0^\infty) = f(1^\infty) = 0. \)

In the analysis of the zero temperature case for these functions, the exponential limit of \( P(\beta f) \) plays an important role.

Lemma 6. If \( f \in W \) satisfies (11), then
\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(P(\beta f)) = A
\]
where
\[
A = \begin{cases} 
  b + d + \sum_{j=1}^{\infty} c_{1+j}, & \text{when } \sum_{j=1}^{\infty} a_{1+j} \leq b + d + \sum_{j=1}^{\infty} c_{1+j}, \\
  b + d + \sum_{j=1}^{\infty} a_{1+j}, & \text{when } \sum_{j=1}^{\infty} c_{1+j} \leq b + d + \sum_{j=1}^{\infty} a_{1+j}, \\
  \frac{h d}{2} + \sum_{j=1}^{\infty} \frac{a_{1+j}}{2} + \sum_{j=1}^{\infty} \frac{c_{1+j}}{2}, & \text{in the other cases.}
\end{cases}
\]

Proof. See Prop. 12 in [2].

Given \( f \in W \) satisfying (11) and \( \beta > 0 \), in order to simplify the computations, we will consider the function \( H_\beta(x) = \frac{h(x)}{h_\beta(0^\infty)} \). This normalization of the eigenfunction was used in [2]. Observe that \( H_\beta(0^\infty) = 1 \) and \( \log(H_\beta) - \log(H_\beta \circ \sigma) = \log(h_\beta) - \log(h_\beta \circ \sigma) \). Therefore
\[
g_\beta = \beta f + \log(h_\beta) - \log(h_\beta \circ \sigma) - P(\beta f) = \beta f + \log(h_\beta) - \log(H_\beta \circ \sigma) - P(\beta f).
\]
Following [21] (see Theo. 3.1 and page 1341), we obtain

\[ H_\beta(0^\infty) = 1 \]

\[ H_\beta(1^\infty) = \frac{e^{\beta b}}{e^{P(\beta f)}} \left( 1 + \sum_{j=1}^{\infty} e^{\beta(a_{1+j} + ...+ a_{1+j}) - j P(\beta f)} \right) \]

\[ H_\beta|_{[0^q]} = \frac{(e^{P(\beta f)} - 1)}{e^{P(\beta f)}} \left( 1 + \sum_{j=1}^{\infty} e^{\beta(a_{1+j} + ...+ a_{1+j}) - j P(\beta f)} \right), \quad q \geq 1 \]

\[ H_\beta|_{[1^q]} = \frac{H_\beta(1^\infty)(e^{P(\beta f)} - 1)}{e^{P(\beta f)}} \left( 1 + \sum_{j=1}^{\infty} e^{\beta(c_{q+j} + ...+ c_{q+j}) - j P(\beta f)} \right), \quad q \geq 1. \]

The next lemma can be used in order to get the function \( R_+^\infty \) that appears in the formulation of the deviation function in Theorem 1.

**Lemma 7.** Under the above notations, for \( f \in W \) satisfying (11), there exists the uniform limit \( U = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(H_\beta) \). This function \( U \) is a calibrated subaction for \( f \) and satisfies

\[ U(0^\infty) = 0, \]

\[ U(1^\infty) = b + \max \left\{ 0, \sum_{j=1}^{\infty} (a_{1+j}) - A \right\}, \]

\[ U|_{[0^q]} = A + \max \left\{ 0, \sum_{j=1}^{\infty} (a_{q+j}) - A \right\}, \quad q \geq 1, \]

\[ U|_{[1^q]} = b + A + \max \left\{ 0, \sum_{j=1}^{\infty} (a_{1+j}) - A \right\} + \max \left\{ 0, \sum_{j=1}^{\infty} (c_{q+j}) - A \right\}, \quad q \geq 1. \]

**Proof.** The result can be obtained as a particular case of Prop. 2 in [2].

**Remark:** if \( V = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(h_\beta) \) then \( U = V - C \), with \( C = V(0^\infty) \).

We want to study the L.D.P. for the equilibrium measures \( \mu_\beta \) and naturally any maximizing measure of \( f \in W \) is a convex combination of the ergodic measures supported in the periodic orbits \( 0^\infty = (000... \) and \( 1^\infty = (111...) \). From the above lemma there exists the limit function

\[ R_+ = - \lim_{\beta \to +\infty} \frac{g_\beta}{\beta} = -f - U + U \circ \sigma + m(f) = -f - U + U \circ \sigma. \]

We want to use Theorem 1. In order to do that we need to find the expression of deviation function. More precisely, we need to compute \( I(0^\infty) \) and \( I(1^\infty) \). In this way, considering the Lemma 2 we first study \( \mu_\beta([0^n]) \) and \( \mu_\beta([1^n]) \).
Lemma 8. Let \( f \in W \) satisfying (11). Then, for \( \beta > 0 \) and \( n \geq 1 \),

\[
\mu_{\beta}([0^n]) = \frac{S_0^\beta([0^n])}{S_0^\beta(S_0^\beta + S_1^\beta)} \quad \text{and} \quad \mu_{\beta}([1^n]) = \frac{S_1^\beta([1^n])}{S_0^\beta(S_0^\beta + S_1^\beta)},
\]

where

\[
S_0^\beta = S_0^1(\beta) := \frac{1 + \sum_{j=1}^{\infty}(j + 1) e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta)f}}{1 + \sum_{j=1}^{\infty} e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta)f}},
\]

\[
S_1^\beta = S_1^1(\beta) := \frac{1 + \sum_{j=1}^{\infty}(j + 1) e^{\beta(c_2 + \ldots + c_{j+1}) - jP(\beta)f}}{1 + \sum_{j=1}^{\infty} e^{\beta(c_2 + \ldots + c_{j+1}) - jP(\beta)f}},
\]

and for \( n \geq 2 \)

\[
S_0^n(\beta) := \frac{e^{P(\beta)f} \sum_{j=n}^{\infty}(j - n + 1) e^{\beta(a_2 + \ldots + a_j) - jP(\beta)f}}{(1 + \sum_{i=1}^{\infty} e^{\beta(a_2 + \ldots + a_{i+1}) - jP(\beta)f})},
\]

\[
S_1^n(\beta) := \frac{e^{P(\beta)f} \sum_{j=n}^{\infty}(j - n + 1) e^{\beta(c_2 + \ldots + c_j) - jP(\beta)f}}{(1 + \sum_{i=1}^{\infty} e^{\beta(c_2 + \ldots + c_{i+1}) - jP(\beta)f})}.
\]

Proof. Following [2], page 1351,

\[
S_0^\beta := \frac{1 + \sum_{j=1}^{\infty}(j + 1) e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta)f}}{1 + \sum_{j=1}^{\infty} e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta)f}}
\]

\[
= 1 + \sum_{j=2}^{\infty} e^{\beta(a_2 + \ldots + a_j) + \log(H_\beta[001]) - \log(H_\beta[01]) - (j - 1)P(\beta)f}
\]

and

\[
S_1^\beta := \frac{1 + \sum_{j=1}^{\infty}(j + 1) e^{\beta(c_2 + \ldots + c_{j+1}) - jP(\beta)f}}{1 + \sum_{j=1}^{\infty} e^{\beta(c_2 + \ldots + c_{j+1}) - jP(\beta)f}}
\]

\[
= 1 + \sum_{j=2}^{\infty} e^{\beta(c_2 + \ldots + c_j) + \log(H_\beta[10]) - \log(H_\beta[11]) - (j - 1)P(\beta)f}.
\]

For \( j \geq 2 \), (see page 1352 in [2])

\[
\mu_{\beta}([0^n]) = \mu_{\beta}([0]) e^{\beta(a_2 + \ldots + a_j) + \log(H_\beta[001]) - \log(H_\beta[01]) - (j - 1)P(\beta)f} \quad (13)
\]

and

\[
\mu_{\beta}([1^n]) = \mu_{\beta}([10]) e^{\beta(c_2 + \ldots + c_j) + \log(H_\beta[110]) - \log(H_\beta[11]) - (j - 1)P(\beta)f} \quad (14)
\]
Then
\[ \mu_\beta([0]) = \sum_{j=1}^{\infty} \mu_\beta([0^j1]) = \mu_\beta([01]) S_0(\beta), \]

and
\[ \mu_\beta([1]) = \sum_{j=1}^{\infty} \mu_\beta([1^j0]) = \mu_\beta([10]) S_1(\beta). \]

As \( \mu_\beta([01]) = \mu_\beta([10]) \) (because \( \mu_\beta \) is \( \sigma \)-invariant) and \( \mu_\beta([0]) + \mu_\beta([1]) = 1 \) we obtain
\[ \mu_\beta([01]) = \mu_\beta([10]) = \frac{1}{S_0(\beta) + S_1(\beta)}. \] (15)

As a consequence,
\[ \mu_\beta([0]) = \frac{S_0(\beta)}{S_0(\beta) + S_1(\beta)} \text{ and } \mu_\beta([1]) = \frac{S_1(\beta)}{S_0(\beta) + S_1(\beta)}. \]

From (13) and (15), for any \( n \geq 2 \),
\[ \mu_\beta([0^n]) = \sum_{j=n}^{\infty} \mu_\beta([0^j1]) \]
\[ = \mu_\beta([01]) \sum_{j=n}^{\infty} e^{\beta(a_2 + \ldots + a_j) + \log(H_\beta|_{0\omega_1}) - \log(H_\beta|_{01}) - (j-1)P(\beta f)} \]
\[ = \sum_{j=n}^{\infty} \frac{e^{\beta(a_2 + \ldots + a_j) + \log(H_\beta|_{0\omega_1}) - \log(H_\beta|_{01}) - (j-1)P(\beta f)}}{S_0(\beta) + S_1(\beta)}. \]

Furthermore,
\[ \sum_{j=n}^{\infty} e^{\beta(a_2 + \ldots + a_j) + \log(H_\beta|_{0\omega_1}) - \log(H_\beta|_{01}) - (j-1)P(\beta f)} \]
\[ = \sum_{j=n}^{\infty} \frac{e^{\beta(a_2 + \ldots + a_j) - (j-1)P(\beta f)} H_\beta|_{0\omega_1}}{(1 + \sum_{i=1}^{\infty} e^{\beta(a_2 + \ldots + a_{j+i}) - iP(\beta f)})} \]
\[ = \sum_{j=n}^{\infty} \sum_{i=0}^{\infty} \frac{e^{\beta(a_2 + \ldots + a_{j+i}) - (j+i-1)P(\beta f)}}{(1 + \sum_{i=1}^{\infty} e^{\beta(a_2 + \ldots + a_{j+i}) - iP(\beta f)})} \]
\[ = e^{P(\beta f)} \frac{\sum_{m=n}^{\infty} e^{\beta(a_2 + \ldots + a_m) - mP(\beta f)}}{(1 + \sum_{i=1}^{\infty} e^{\beta(a_2 + \ldots + a_{j+i}) - iP(\beta f)})} = S_0^n(\beta). \]
Therefore, we finally get
\[ \mu_{\beta}[0^n] = \frac{S^n_0(\beta)}{S_0(\beta) + S_1(\beta)}. \]
The computation for \( \mu_{\beta}[1^n] \) is similar.

As we want to determine the limit of \( \frac{1}{\beta} \log(\mu_{\beta}([0^n])) \) and \( \frac{1}{\beta} \log(\mu_{\beta}([1^n])) \) (see Lemma 2) the next lemma is useful.

**Lemma 9.** Let \( f \in \mathcal{W} \) satisfying (11). Denote \( A = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(P(\beta f)). \) Under the above notations,

\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_0(\beta)) = \max\{0, \sum_{j=2}^{\infty} a_j - 2A\} - \max\{0, \sum_{j=2}^{\infty} a_j - A\}, \]

\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_1(\beta)) = \max\{0, \sum_{j=2}^{\infty} c_j - 2A\} - \max\{0, \sum_{j=2}^{\infty} c_j - A\} \]

and for \( n \geq 2 \)

\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S^n_0(\beta)) = \max\{a_2 + \ldots + a_n, \sum_{j=2}^{\infty} a_j - 2A\} - \max\{0, \sum_{j=2}^{\infty} a_j - A\}, \]

\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S^n_1(\beta)) = \max\{c_2 + \ldots + c_n, \sum_{j=2}^{\infty} c_j - 2A\} - \max\{0, \sum_{j=2}^{\infty} c_j - A\}. \]

**Proof.** We only present the prove of the first equation, because the arguments are similar for the other cases. Initially, observe that for any \( j_1 \geq 0, \)

\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log \left( \sum_{j \geq j_1} (j+1)e^{-jP(\beta f)} \right) = -2A \]

and

\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log \left( \sum_{j \geq j_1} e^{-jP(\beta f)} \right) = -A \]

(see Cor. 14 in [2]).
As
\[ \frac{1}{\beta} \log(S_0(\beta)) = \frac{1}{\beta} \log[1 + \sum_{j=1}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)}] \]
\[ - \frac{1}{\beta} \log[1 + \sum_{j=1}^{\infty} e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)}], \]
we will study the limit for \( \frac{1}{\beta} \log[1 + \sum_{j=1}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)}] \) and \( \frac{1}{\beta} \log[1 + \sum_{j=1}^{\infty} e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)}] \).

As \( a_i < 0 \ \forall \ i \in \{2, 3, 4, \ldots\} \) we have,
\[ \liminf_{\beta \to +\infty} \frac{1}{\beta} \log \left( 1 + \sum_{j=1}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)} \right) \geq \max \left\{ 0, \liminf_{\beta \to +\infty} \frac{1}{\beta} \log \left( e^{\beta \sum_{i \geq 2} a_i} \sum_{j=1}^{\infty} (j + 1)e^{-jP(\beta_f)} \right) \right\} \]
\[ = \max\{0, \sum_{i \geq 2} a_i - 2A\}. \]

Furthermore, for any fixed \( j_0 \), rewriting
\[ \left( 1 + \sum_{j=1}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)} \right) \]
in the form
\[ \left[ 1 + \sum_{j=1}^{j_0-1} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)} \right] + \left[ \sum_{j=j_0}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)} \right] \]
we have
\[ \limsup_{\beta \to +\infty} \frac{1}{\beta} \log \left( 1 + \sum_{j=1}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)} \right) \]
\[ = \max \left\{ 0, \limsup_{\beta \to +\infty} \frac{1}{\beta} \log \left( \sum_{j=j_0}^{\infty} (j + 1)e^{\beta(a_2 + \ldots+a_1+j)-jP(\beta_f)} \right) \right\} \]
\[ \leq \max \left\{ 0, \limsup_{\beta \to +\infty} \frac{1}{\beta} \log \left( e^{\beta(a_2 + \ldots+a_{j_0})} \sum_{j=j_0}^{\infty} (j + 1)e^{-jP(\beta_f)} \right) \right\} \]
\[ = \max\{0, a_2 + \ldots + a_{j_0} - 2A\}. \]
Thus, as we can consider $j_0$ large enough,
\[
\limsup_{\beta \to +\infty} \frac{1}{\beta} \log \left( 1 + \sum_{j=1}^{\infty} (j + 1) e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta f)} \right) \leq \max \{ 0, \sum_{j=2}^{\infty} a_j - 2A \}.
\]
The conclusion is that
\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log \left( 1 + \sum_{j=1}^{\infty} (j + 1) e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta f)} \right) = \max \{ 0, \sum_{j=2}^{\infty} a_j - 2A \}.
\]

With similar arguments we obtain
\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log \left( 1 + \sum_{j=1}^{\infty} e^{\beta(a_2 + \ldots + a_{j+1}) - jP(\beta f)} \right) = \max \{ 0, \sum_{j=2}^{\infty} a_j - A \}.
\]

Now we show that the family of measures $\mu_\beta$ satisfies a L.D.P. and present the expression of the deviation function. We remark that, when the maximizing measure of a potential $f$ is unique, the deviation function in [3] is equal to $R_+^\infty$. For the class of potentials that we consider in this section, we have $R_+^\infty(0^\infty) = R_+^\infty(1^\infty) = 0$. However in the theorem below $I(0^\infty) \neq 0$, which means, $I \neq R_+^\infty$ (see also Theo. 3 and page 1343 in [2]).

**Theorem 10.** Let $f \in W$ satisfying [L1]. Suppose $\sum_{j \geq 2} a_j < b + d + \sum_{j \geq 2} c_j$. Then $(\mu_\beta)_{\beta > 0}$ satisfies a Large Deviation Principle with deviation function $I$ defined by
\[
I(0^\infty) = b + d + \sum_{j \geq 2} c_j - \sum_{j \geq 2} a_j, \quad I(1^\infty) = 0
\]
and for any $x \in \{0, 1\}^\mathbb{N}$,
\[
I(x) = \begin{cases} R_+^n(x) + I(0^\infty) & \text{if } x = (x_1 \ldots x_n 0^\infty) \\ R_+^n(x) & \text{if } x = (x_1 \ldots x_n 1^\infty) \\ +\infty & \text{else} \end{cases}
\]
where $R_+ = -f - U + U \circ \sigma$ and $U$ satisfies
\[
U(0^\infty) = 0, \quad U|_{[0^1]} = \max \left\{ b + d + \sum_{j=2}^{\infty} c_j, \sum_{j=1}^{\infty} a_{q+j} \right\}, \quad q \geq 1,
\]
\[
U(1^\infty) = b, \quad \text{and} \quad U|_{[1^0]} = b + \sum_{j=1}^{\infty} c_{q+j}, \quad q \geq 1.
\]
Proof. First note that, with the hypothesis \( \sum_{j \geq 2} a_j < b + d + \sum_{j \geq 2} c_j \), from Lemma 6, \( A := \lim_{\beta \to +\infty} \frac{1}{\beta} \log(P(\beta f)) = b + d + \sum_{j \geq 2} c_j \). Then,

\[
\sum_{j \geq 2} a_j < A < \sum_{j \geq 2} c_j \tag{16}
\]

and this function \( U \) coincides with the one in Lemma 7, which means, \( U = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(H_\beta) \). Particularly, \( R_+ = -f - U \circ \sigma \) is the uniform limit of \( -\frac{g_\beta}{\beta} \), when \( \beta \to +\infty \).

**Claim:**

\[
\lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([0^n])) = \sum_{j \geq 2} a_j - A
\]

and

\[
\lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([1^n])) = 0.
\]

Indeed, from (16), Lemma 8 and Lemma 9 we get, for \( n \) large enough,

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([0^n])) = \lim_{\beta \to +\infty} \frac{1}{\beta} \log \left( \frac{S_0^n(\beta)}{S_0(\beta) + S_1(\beta)} \right)
\]

\[
= \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_0^n(\beta)) - \max \left\{ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_0(\beta)), \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_1(\beta)) \right\}
\]

\[
= \left[ \sum_{j=2}^{\infty} a_j - 2A \right] - \max \left\{ \max\{0, \sum_{j=2}^{\infty} a_j - 2A \}, -A \right\}
\]

\[
= \left[ \sum_{j=2}^{\infty} a_j - 2A \right] - (-A) = \sum_{j=2}^{\infty} a_j - A
\]

and

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([1^n])) = \lim_{\beta \to +\infty} \frac{1}{\beta} \log \left( \frac{S_1^n(\beta)}{S_0(\beta) + S_1(\beta)} \right)
\]

\[
= \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_1^n(\beta)) - \max \left\{ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_0(\beta)), \lim_{\beta \to +\infty} \frac{1}{\beta} \log(S_1(\beta)) \right\}
\]

\[
= (-A) - (-A) = 0.
\]

This concludes the proof of claim.
Let \( I : X \to [0, +\infty] \) be defined by

\[
I(0^\infty) = - \lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([0^n])) = b + d + \sum_{j \geq 2} c_j - \sum_{j \geq 2} a_j,
\]

\[
I(1^\infty) = - \lim_{n \to +\infty} \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([1^n])) = 0
\]

and, for any \( x = (x_1 x_2 x_3 \ldots), \ x \notin \{0^\infty, 1^\infty\}, \)

\[
I(x) = \inf_{y \in \{0^\infty, 1^\infty\}} \lim_{n \to +\infty} \inf \left( R_n^a(x_1 \ldots x_n y) + I(y) \right). \tag{17}
\]

(\text{It can be checked that equation (17) is satisfied for } x = 0^\infty \text{ and } x = 1^\infty, \text{ but this is not necessary}).

For any cylinder \( k \subset \{0, 1\}^\mathbb{N} \), we claim that

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta(k)) = - \inf_{x \in k} I(x). \tag{18}
\]

Indeed, for a given cylinder \( k_0 \), from (3), the family \( \left( \frac{1}{\beta} \log(\mu_\beta(k_0)) \right) \) is bounded. If for a sequence \( \beta_i \to +\infty \), we have that \( \frac{1}{\beta_i} \log(\mu_{\beta_i}(k_0)) \) converges, then (following the Remark 3., which appears below the Theorem 1) for some subsequence \( \beta_{ij} \) of \( \beta_i \) and for any cylinder \( k \subset X \), we have

\[
\lim_{\beta_{ij} \to +\infty} \frac{1}{\beta_{ij}} \log(\mu_{\beta_{ij}}(k)) = - \inf_{x \in k} I(x).
\]

Particularly, we get

\[
\lim_{\beta_i \to +\infty} \frac{1}{\beta_i} \log(\mu_{\beta_i}(k_0)) = \lim_{\beta_{ij} \to +\infty} \frac{1}{\beta_{ij}} \log(\mu_{\beta_{ij}}(k_0)) = - \inf_{x \in k_0} I(x).
\]

This argument proves that

\[
\lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta(k_0)) = - \inf_{x \in k_0} I(x),
\]

which concludes the proof of (18).

Now we study the function \( I \). Given a point \( x = (x_1 x_2 x_3 \ldots) \) for which 01 occurs infinitely many times, we have \( I(x) = +\infty \) because \( I \geq R_+^{1^\infty} \) and for each occurrence of 01 in \( x \),

\[
R_+(01 x_s x_{s+1} \ldots) = -b - U(01 x_s \ldots) + U(1 x_s \ldots)
\]

\[
\geq -b - (b + d + \sum_{j \geq 2} c_j) + (b + \sum_{j \geq 2} c_j)
\]

\[
= -b - d > 0.
\]

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Then, from (9),

\[ I(x) = \begin{cases} R^n_+(x) + I(0^\infty) & \text{if } x = (x_1...x_n0^\infty) \\ R^n_+(x) + I(1^\infty) & \text{if } x = (x_1...x_n1^\infty) \\ +\infty & \text{else} \end{cases} \]

Assuming \( \sum_{j \geq 2} c_j < b + d + \sum_{j \geq 2} a_j \) we get a symmetric result.

**Theorem 11.** Let \( f \in \mathcal{W} \) satisfying (12). Suppose \( \sum_{j \geq 2} a_j \geq b + d + \sum_{j \geq 2} c_j \) and \( \sum_{j \geq 2} c_j \geq b + d + \sum_{j \geq 2} a_j \). Then, \( \mu_\beta \) satisfies a Large Deviation Principle with deviation function \( I(x) = R^n_+(x) \). More precisely,

\[ I(0^\infty) = 0, \quad I(1^\infty) = 0 \]

and for any \( x \in \{0, 1\}^N \),

\[ I(x) = \begin{cases} R^n_+(x) & \text{if } x = (x_1...x_n0^\infty) \text{ or } x = (x_1...x_n1^\infty) \\ +\infty & \text{else} \end{cases} \]

where \( R_+ = -f - U + U \circ \sigma \) and \( U \) satisfies

\[
\begin{align*}
U(0^\infty) &= 0, \\
U(1^\infty) &= \frac{b}{2} - \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} a_j - \frac{1}{2} \sum_{j \geq 2} c_j, \\
U(0^q1z) &= \sum_{j \geq 1} a_{q+j}, \\
U(1^q0z) &= \frac{b}{2} - \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} a_j - \frac{1}{2} \sum_{j \geq 2} c_j + \sum_{j \geq 1} c_{q+j}.
\end{align*}
\]

**Remark:** The above formulas for \( U \) can have a more symmetric expression if we add the constant \( \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} c_j \). This is irrelevant when we consider the coboundary \( U - U \circ \sigma \) in \( R_+ \). Thus we can consider \( U \) defined by the formulas

\[
\begin{align*}
U(0^\infty) &= \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} c_j, \\
U(1^\infty) &= \frac{b}{2} + \frac{1}{2} \sum_{j \geq 2} a_j, \\
U(0^q1z) &= \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} c_j + \sum_{j \geq 1} a_{q+j}, \\
U(1^q0z) &= \frac{b}{2} + \frac{1}{2} \sum_{j \geq 2} a_j + \sum_{j \geq 1} c_{q+j}.
\end{align*}
\]
Proof. We remark that in the present case (see Lemma 6),
\[ A = \lim_{\beta \to +\infty} \frac{1}{\beta} \log(P(\beta f)) = \frac{b + d}{2} + \sum_{j=1}^{\infty} \frac{a_{1+j}}{2} + \sum_{j=1}^{\infty} \frac{c_{1+j}}{2}. \]

The proof of this theorem follows the same lines of the above one. We only present some of the steps.

First: \( I(0^n) = I(1^n) = 0 \). Indeed, as
\[ \sum_{j \geq 2} a_j \geq A \geq 2A, \quad \sum_{j \geq 2} c_j \geq A \geq 2A, \]
then, from lemmas 8 and 9 we get, for \( n \) large enough,
\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([0^n])) = -A - \max\{-A, -A\} = 0 \]
and, similarly,
\[ \lim_{\beta \to +\infty} \frac{1}{\beta} \log(\mu_\beta([1^n])) = -A - \max\{-A, -A\} = 0. \]

Second: given a point \( x = (x_1 x_2 x_3 \ldots) \) in which 01 occurs infinitely many times, we have \( I(x) = +\infty \). Indeed, as in this case we have 10 occurring infinitely many times too, considering \( R_\infty^+(x) \), for each occurrence of 01 or 10 in \( x \), we get
\[ R_+^0 x_s x_{s+1} \ldots \geq -b - \sum_{j \geq 2} a_j + \left( \frac{b}{2} - \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} a_j - \frac{1}{2} \sum_{j \geq 2} c_j + \sum_{j \geq 1} c_{1+j} \right) \]
\[ = \frac{1}{2} \left( \sum_{j \geq 2} c_j - b - d - \sum_{j \geq 2} a_j \right) \geq 0; \]
\[ R_+^1 x_s x_{s+1} \ldots \geq -d - \left( \frac{b}{2} - \frac{d}{2} + \frac{1}{2} \sum_{j \geq 2} a_j + \frac{1}{2} \sum_{j \geq 2} c_j + \sum_{j \geq 2} a_j \right) \]
\[ = \frac{1}{2} \left( \sum_{j \geq 2} a_j - b - d - \sum_{j \geq 2} c_j \right) \geq 0. \]

This numbers are not zero simultaneously, because their sum results in \(-b-d\). Therefore \( R_\infty^+(x) = +\infty \).
From this computations we conclude that the deviation function satisfies,

\[ I(x) = \begin{cases} 
0 & \text{if } x = 0^\infty \text{ or } x = 1^\infty \\
R^M_+(x) & \text{if } x = (x_1...x_n0^\infty) \text{ or } x = (x_1...x_n1^\infty) \\
+\infty & \text{else}
\end{cases} \]

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