Weak Type Inequalities for Maximal Operators Associated to Double Ergodic Sums

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Weak type inequalities for maximal operators associated to double ergodic sums

Paul Hagelstein and Alexander Stokolos

Abstract. Given an approach region \( \Gamma \in \mathbb{Z}^2_+ \) and a pair \( U, V \) of commuting nonperiodic measure preserving transformations on a probability space \( (\Omega, \Sigma, \mu) \), it is shown that either the associated multiparameter ergodic averages of any function in \( L^1(\Omega) \) converge a.e. or that, given a positive increasing function \( \phi \) on \([0, \infty)\) that is \( o(\log x) \) as \( x \to \infty \), there exists a function \( g \in L^\phi(\mathbb{L})(\Omega) \) whose associated multiparameter ergodic averages fail to converge a.e.

Contents

1. Introduction ............................. 233
2. Weak type (1,1) bounds associated to monotonic approach regions 235
3. Nonmonotonic approach regions .................. 240
References .................................. 249

1. Introduction

Let \( U \) and \( V \) be two commuting measure preserving transformations on a probability space \( (\Omega, \Sigma, \mu) \). The general behavior of the multiparameter ergodic averages associated to \( U \) and \( V \) is becoming well understood. As was proven by N. Dunford in [2] and A. Zygmund in [13], if \( f \in L \log L(\Omega) \) then

\[
\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^jV^k\omega)
\]

converges for a.e. \( \omega \). If the pair \( U, V \) is nonperiodic in the sense that, for any \( (m, n) \neq (0, 0), (m, n) \in \mathbb{Z}^2 \) we have \( \mu \{ \omega \in \Omega : U^mV^n\omega = \omega \} = 0 \), then the \( L \log L \) condition is sharp: as was shown in [6], if \( \phi \) is a positive increasing...
function on \([0, \infty)\) that is \(o(\log x)\) as \(x \to \infty\), then there exists \(g \in L\phi(L)\) such that
\[
\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} g(U^j V^k \omega)
\]
fails to converge a.e. As expected, these convergence and divergence results are reflected in the behavior of the associated ergodic strong maximal operator \(M_S\), defined by
\[
M_S f(\omega) = \sup_{m,n \geq 1} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} |f(U^j V^k \omega)|.
\]
In \([3]\), Fava showed that \(M_S\) satisfies the weak type \((L \log L, L^1)\) inequality
\[
\mu \{ \omega \in \Omega : M_S f(\omega) > \alpha \} \leq \int_{\Omega} \frac{|f|}{\alpha} \left(1 + \log^+ \frac{|f|}{\alpha}\right).
\]
The sharpness of this result was proved in \([6]\), where it was shown that, given a pair of commuting nonperiodic measure preserving transformations \(U\) and \(V\) on \(\Omega\) and an \(o(\log x)\) function \(\phi\) as above, there exists a function \(g \in L\phi(L)\) such that the associated ergodic maximal operator \(M_S g\) is infinite a.e.

This paper is concerned with somewhat better behaved multiparameter ergodic maximal operators, corresponding to improved a.e. convergence results. The maximal operators and corresponding ergodic averages associated to rare bases, ergodic theory analogues of bases associated to geometric rare maximal operators previously studied by Hagelstein, Hare, and Stokolos (see, e.g., \([5]\), \([7]\), and \([11]\)). Being more specific, let \(\Gamma \subset \mathbb{Z}_2^2\) be an unbounded region. (Such a set \(\Gamma\) is sometimes referred to as an approach region as it has a close connection to approach regions associated to boundary value problems arising in harmonic analysis, complex variables, and partial differential equations.) The corresponding ergodic maximal operator \(M_\Gamma\) is given by
\[
M_\Gamma f(\omega) = \sup_{(m,n) \in \Gamma} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} |f(U^j V^k \omega)|.
\]
(Note if \(\Gamma = \mathbb{Z}_2^2\) itself, then \(M_\Gamma\) is the usual strong ergodic maximal operator \(M_S\).

In this paper we will show that, given \(\Gamma\), if \(U, V\) is a commuting pair of nonperiodic measure preserving transformations one of two possibilities must occur:

(i) \(M_\Gamma\) is of weak type \((1, 1)\) and accordingly the associated rare ergodic averages
\[
\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^j V^k \omega)
\]
converge a.e. for every \(f \in L^1(\Omega)\); or
(ii) $M_\Gamma$ is of weak type $(L \log L, L^1)$ but such that, given a positive increasing function $\phi$ on $[0, \infty)$ that is $o(\log x)$ for $x \to \infty$, there exists $g \in L\phi(L)$ satisfying $M_\Gamma g = \infty$ a.e. and such that

$$\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} g(U^j V^k \omega)$$

fails to converge a.e.

We shall see that a monotonicity condition on $\Gamma$ determines whether case (i) or (ii) holds. The notion of monotonicity is defined as follows. For any positive integer $j$, let $j^*$ be the integer satisfying $2^{j^*} - 1 < j \leq 2^{j^*}$. Given a set $\Gamma \subset \mathbb{Z}_+^2$, we define the dyadic skeleton $\Gamma^*$ of $\Gamma$ by

$$\Gamma^* = \{(2^{m^*}, 2^{n^*}) : (m, n) \in \Gamma\}.$$

We say that $\Gamma$ is monotonic if, for any $(m_1, n_1), (m_2, n_2)$ in $\Gamma^*$, $m_1 < m_2$ implies $n_1 \leq n_2$. We will prove that if $\Gamma$ is contained in a finite union of monotonic sets then case (i) holds, and otherwise case (ii) will hold.

2. Weak type $(1,1)$ bounds associated to monotonic approach regions

We now show that the ergodic maximal operator $M_\Gamma$ associated to a monotonic region $\Gamma \subset \mathbb{Z}_+^2$ is of weak type $(1,1)$. To prove this theorem, we will “transfer” the known weak type $(1,1)$ bound of a geometric maximal operator associated to a monotonic basis of rectangles to a weak type $(1,1)$ bound of $M_\Gamma$. The transference mechanism will be constructed explicitly, taking advantage of a lemma of Katznelson and Weiss involving commuting nonperiodic pairs of measure preserving transformations. We hope to yield a general transference principle relating weak type bounds of “rare” multi-parameter ergodic maximal operators associated to commuting nonperiodic pairs of measure preserving transformations to weak type bounds of rare geometric maximal operators on a future occasion.

**Lemma 1.** Let $\Gamma \subset \mathbb{Z}_+^2$ be a monotonic region and let $U, V$ be a pair of commuting nonperiodic measure preserving transformations on a probability space $(\Omega, \Sigma, \mu)$. Then the associated maximal operator $M_\Gamma$ satisfies the weak type $(1,1)$ inequality

$$\mu \{\omega \in \Omega : M_\Gamma f(\omega) > \alpha\} \leq \frac{C}{\alpha} \int_{\Omega} |f|.$$

**Proof.** Let $\Gamma^*$ denote the dyadic skeleton of $\Gamma$. One may readily check that $M_\Gamma f \leq 4M_{\Gamma^*} f$, hence it suffices to show that $M_{\Gamma^*}$ is of weak type $(1,1)$.

Since $\Gamma$ is monotonic, we may write $\Gamma^* = \{(m_1, n_1), (m_2, n_2), \ldots\}$ where $(m_j, n_j) = (2^{m^*_j}, 2^{n^*_j})$ and where $m_j \leq m_{j+1}, n_j \leq n_{j+1}$ for each $j$. Also let
\( \Gamma_j^* = \{(m_1, n_1), \ldots, (m_j, n_j)\} \). As
\[
\lim_{j \to \infty} \mu \left\{ \omega \in \Omega : M_{\Gamma_j^*} f(\omega) > \alpha \right\} = \mu \left\{ \omega \in \Omega : M_{\Gamma^*} f(\omega) > \alpha \right\}
\]
there exists \( N \) such that
\[
\mu \left\{ \omega \in \Omega : M_{\Gamma_N^*} f(\omega) > \alpha \right\} \geq \frac{1}{2} \mu \left\{ \omega \in \Omega : M_{\Gamma^*} f(\omega) > \alpha \right\}.
\]
For notational simplicity we shall denote \( M_{\Gamma_N^*} \) by \( M^* \). It suffices to show
\[
(1) \quad \mu \left\{ \omega \in \Omega : M^* f(\omega) > \alpha \right\} \leq \frac{C}{\alpha} \int_{\Omega} |f|,
\]
where \( C \) is independent of \( N \).

It is useful at this point to recall the following result of Katznelson and Weiss:

**Lemma 2** ([9]). Let \( U \) and \( V \) be two commuting nonperiodic measure preserving transformations on a measure space \( \Omega \) of finite measure. Then for any \( \epsilon > 0 \) and positive integer \( \gamma \) there exist sets \( B \) and \( E \) in \( \Omega \) such that
\[
\mu (\Omega - E) < \epsilon \quad \text{and} 
\]
\[
\Omega = \left( \bigcup_{j,k=0}^{\gamma-1} U^{j,k} A \right) \cup E,
\]
where the \( B^{j,k} = U^j V^k B \) are pairwise disjoint.

Let \( \epsilon = \frac{1}{4} \mu \left\{ \omega : M^* f(\omega) > \alpha \right\} \). We assume without loss of generality that \( \epsilon > 0 \). Set \( R_N = \max(m_N, n_N) \). Let \( \gamma \in \mathbb{Z}_+ \) be such that \( \frac{2R_N}{\epsilon} < \gamma \).

By Lemma 2, there exists a set \( A \) such that \( \{U^{j,k}A\}_{j,k=0}^{\gamma-1} \) is a disjoint sequence of sets in \( \Omega \) such that \( \mu \left( \bigcup_{j,k=0}^{\gamma-1} U^{j,k} A \right) > 1 - \epsilon \). Observe that
\[
1 - \epsilon < \gamma^2 \mu(A) \leq 1 \quad \text{and hence}
\]
\[
\mu \left( \bigcup_{j,k=0}^{\gamma-1} U^{j,k} A \right) = (\gamma - R_N)^2 \mu(A) \\
\geq \gamma^2 \mu(A) - 2R_N \gamma \mu(A) \\
> (1 - \epsilon) - (\epsilon \gamma) \gamma \mu(A) \\
\geq 1 - 2\epsilon.
\]

Accordingly,
\[
\mu \left( \left\{ \omega : M^* f(\omega) > \alpha \right\} \cap \bigcup_{j,k=0}^{\gamma-1-R_N} U^{j,k} A \right) \geq \frac{1}{2} \mu \left\{ \omega : M^* f(\omega) > \alpha \right\}.
\]
For \( s = 1, 2, \ldots, N \) let
\[
E_s = \left\{ \omega \in \Omega : \frac{1}{m_s n_s} \sum_{j=0}^{m_s-1} \sum_{k=0}^{n_s-1} |f(U^j V^k \omega)| > \alpha \right\}.
\]
and let \( A_{s,j,k} = A \cap U^{-j} V^{-k} E_s \).

We now let \( \{B_r\}_{r=1}^{\tilde{N}} \) be a disjoint collection of sets of positive measure such that:

(i) \( \bigcup_{r=1}^{\tilde{N}} B_r = \bigcup_{s=1}^N \bigcup_{j,k=0}^{\gamma - 1 - R_N} A_{s,j,k} \), and

(ii) given any \( B_r \) and \( A_{s,j,k} \) for \( 1 \leq r \leq \tilde{N}; 1 \leq s \leq N; \) and \( 1 \leq j, k \leq \gamma - 1 - R_N \), either \( B_r \subseteq A_{s,j,k} \) or \( \mu (B_r \cap A_{s,j,k}) = 0 \).

In order to circumvent certain technical complications later on involving sets of measure zero, we assume without loss of generality that a slightly stronger version of (ii) holds, namely, given any \( B_r \) and \( A_{s,j,k} \) for \( 1 \leq r \leq \tilde{N}; 1 \leq s \leq N; \) and \( 1 \leq j, k \leq \gamma - 1 - R_N \), either \( B_r \subseteq A_{s,j,k} \) or \( B_r \cap A_{s,j,k} = \emptyset \).

This may be justified from removing from the space \( \Omega \) the set of zero measure
\[
\bigcup_{r=1}^{\tilde{N}} \bigcup_{m,n=1}^{\infty} U^m V^n \{ \omega \in B_r \cap A_{s,j,k} : \mu (B_r \cap A_{s,j,k}) = 0 \}.
\]

Note that if \( M^* f(\omega) > \alpha \) and \( \omega \in \bigcup_{j,k=0}^{\gamma - 1 - R_N} U^j V^k A \), then \( \omega \in E_s \) for some \( s \), and hence for some \( 0 \leq j, k \leq \gamma - 1 - R_N \) we have \( U^{-j} V^{-k} \omega \in A_{s,j,k} \). Hence \( U^{-j} V^{-k} \omega \in B_r \) for some \( r \), and thus \( \omega \in U^j V^k B_r \). We will frequently denote \( U^j V^k B_r \) by \( B_{r,j,k} \). So
\[
\mu \left( \{ \omega : M^* f(\omega) > \alpha \} \cap \bigcup_{j,k=0}^{\gamma - 1 - R_N} U^j V^k A \right)
\]
\[
= \mu \left( \{ \omega : M^* f(\omega) > \alpha \} \cap \bigcup_{r=1}^{\tilde{N}} \bigcup_{j,k=0}^{\gamma - 1 - R_N} B_{r,j,k} \right)
\]
\[
= \sum_{r=1}^{\tilde{N}} \mu \left( \{ \omega : M^* f(\omega) > \alpha \} \cap \bigcup_{j,k=0}^{\gamma - 1 - R_N} B_{r,j,k} \right),
\]
the latter equality following from the fact that
\[
\mu \left( \bigcup_{j,k=0}^{\gamma - 1 - R_N} U^j V^k B_r \right) \cap \left( \bigcup_{j,k=0}^{\gamma - 1 - R_N} U^j V^k B_s \right) = 0
\]
when \( r \neq s \).
Fix an \( r \in \{1, \ldots, \tilde{N}\} \). It suffices to show
\[
\mu \left( \{ \omega : M^* f(\omega) > \alpha \} \cap \bigcup_{j,k=0}^{\gamma-1-R_N} B_{r,j,k} \right) \leq \frac{C}{\alpha} \int_{\bigcup_{j,k=0}^{\gamma-1-R_N} B_{r,j,k}} |f| \, d\mu.
\]

For our convenience, we set \( \rho_r = \sqrt{\mu(B_r)} \). Define \( g_r \) on
\[
Q_r := [0, \gamma \rho_r] \times [0, \gamma \rho_r]
\]
by
\[
g_r(\xi, \eta) = \frac{1}{\mu(B_r)} \sum_{j,k=0}^{\gamma-1} \left( \int_{B_{r,j,k}} |f| \, d\mu \right) \chi_{[j \rho_r, (j+1) \rho_r) \times [k \rho_r, (k+1) \rho_r)}(\xi, \eta).
\]

Note that
\[
\int_{Q_r} g_r(\xi, \eta) \, d\xi \, d\eta = \int_{\bigcup_{j,k=0}^{\gamma-1} B_{r,j,k}} |f| \, d\mu.
\]

Let now the collection of rectangles \( \beta_{T_N, r}^* \) be defined by
\[
\beta_{T_N, r}^* = \{ [j \rho_r, (j + m_\ell) \rho_r] \times [k \rho_r, (k + n_\ell) \rho_r] : j, k \in \mathbb{Z}, 1 \leq \ell \leq N \}.
\]

We define the geometric maximal operator \( M_r \) associated to \( \beta_{T_N, r}^* \) by
\[
M_r f(\xi, \eta) = \sup \left\{ \frac{1}{|R|} \int_R |f(u, v)| \, dudv : (\xi, \eta) \in R, R \in \beta_{T_N, r}^* \right\}.
\]

Suppose \( M^* f(\omega) > \alpha \) and \( \omega \in B_{r,j,k} \) for some \( 0 \leq j, k \leq \gamma - 1 - R_N \).
Then \( \omega \in E_s \) and \( U^{-j} V^{-k} \omega \in A_{s,j,k} \) for some \( s \), and hence \( B_r \subset A_{s,j,k} \), implying \( U^j V^k B_r \subset E_s \), i.e. \( B_{r,j,k} \subset E_s \).

So
\[
\frac{1}{\mu(B_r)} \int_{B_{r,j,k}} \sum_{a=0}^{m_a-1} \sum_{b=0}^{n_b-1} f \left( U^a V^b \right) \, d\mu(w) > \alpha.
\]

Hence if \((\xi, \eta) \in [j \rho_r, (j+1) \rho_r) \times [k \rho_r, (k+1) \rho_r)\) for \( 1 \leq j, k \leq \gamma - 1 - R_N \) we have
\[
M_r g_r(\xi, \eta) \geq \frac{1}{m_a n_b \mu(B_r)} \int_{u=j \rho_r}^{(j+m_a) \rho_r} \int_{v=k \rho_r}^{(k+n_b) \rho_r} g_r(u, v) \, dudv
\]
\[
= \frac{1}{m_a n_b \mu(B_r)} \sum_{a=0}^{m_a-1} \sum_{b=0}^{n_b-1} \rho_{r,a}^2 \int_{B_{r,a,b}} |f| \, d\mu
\]
\[
= \frac{1}{m_a n_b \mu(B_r)} \int_{B_{r,j,k}} \sum_{a=0}^{m_a-1} \sum_{b=0}^{n_b-1} f \left( U^a V^b \right) \, d\mu(w) > \alpha.
\]

So \( \{ \omega : M^* f(\omega) > \alpha \} \cap \bigcup_{j,k=0}^{\gamma-1-R_N} B_{r,j,k} \) is a disjoint union of a subcollection of the \( B_{r,j,k} \)'s, and if \( B_{r,j,k} \subset \{ \omega : M^* f(\omega) > \alpha \} \cap \bigcup_{j,k=0}^{\gamma-1-R_N} B_{r,j,k} \)
then
\[ [j\rho_r, (j+1)\rho_r] \times [k\rho_r, (k+1)\rho_r] \subset \{ (x, y) : M_r g_r(x, y) > \alpha \} . \]

As the sets \( B_{r,j,k} \) are of the same measure \( \mu(B_r) \) and disjoint, as well as the sets of the form 
\[ [j\rho_r, (j+1)\rho_r] \times [k\rho_r, (k+1)\rho_r] , \]
we realize
\[ \mu\left( \{ \omega : M^* f(\omega) > \alpha \} \right) \leq \left| \{(\xi, \eta) : M_r g_r(\xi, \eta) > \alpha \} \right| . \]

Hence it suffices to show
\[ \left| \{(\xi, \eta) : M_r g_r(\xi, \eta) > \alpha \} \right| \leq \frac{C}{\alpha} \int_{\cup_{j,k=0}^{\gamma-1} B_{r,j,k}} |f| d\mu . \]

The rectangles in \( \beta_{N,r}^+ \) satisfy the following monotonicity property: if \( R_1, R_2 \in \beta_{N,r}^+ \), then there exists a translate \( \tau R_1 \) of \( R_1 \) such that either \( \tau R_1 \subset 2 \cdot R_2 \) or \( R_2 \subset 2 \cdot \tau R_1 \) where multiplication by 2 means the doubling of the dimensions of the rectangle. This follows from the monotonicity property of \( \Gamma_N \).

Any geometric maximal operator associated to a basis of such rectangles in \( \mathbb{R}^2 \) with sides parallel to the axes is automatically of weak type \((1,1)\), as may be readily seen by the proof of the Vitali covering theorem. (See [12] for more details.) Hence
\[ \left| \{(\xi, \eta) : M_r g_r(\xi, \eta) > \alpha \} \right| \leq \frac{C}{\alpha} \int_{\cup_{j,k=0}^{\gamma-1} B_{r,j,k}} |f| d\mu , \]
as desired.

\[ \square \]

**Theorem 1.** Let \( U \) and \( V \) be a pair of commuting nonperiodic measure preserving transformations on a probability space \((\Omega, \Sigma, \mu)\), and let \( \Gamma \subset \mathbb{Z}_{2,+}^2 \) be contained in a finite number of monotonic sets. Then the associated maximal operator \( M_\Gamma \) satisfies the weak type \((1,1)\) inequality
\[ \mu \{ \omega \in \Omega : M_\Gamma f(\omega) > \alpha \} \leq \frac{C}{\alpha} \int_{\Omega} |f| , \]
and the associated rare ergodic averages
\[ \lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^j V^k \omega) \]
converge a.e. for every \( f \in L^1(\Omega) \).

**Proof.** Since \( \Gamma \subset \mathbb{Z}_{2,+}^2 \) is contained in a finite number of monotonic sets, there exists subsets \( \Gamma^1, \ldots, \Gamma^N \) of \( \mathbb{Z}_{2,+}^2 \) that are monotonic such that \( \Gamma \subset \bigcup_{j=1}^{N} \Gamma^j \).

As each \( M_{\Gamma^j} \) is of weak type \((1,1)\) by Lemma 1 and as by sublinearity we have \( M_{\Gamma} f \leq M_{\Gamma^1} f + \cdots + M_{\Gamma^N} f \), the weak type \((1,1)\) estimate follows.
Let $f \in L^1(\Omega)$ and $\epsilon > 0$. To prove the convergence result, it suffices to show

$$\mu \left\{ \omega \in \Omega : \left( \limsup_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U_j V_k^k \omega) \right) - \left( \liminf_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U_j V_k^k \omega) \right) > \epsilon \right\} < \epsilon.$$  

Let $\epsilon_1 > 0$, where $\epsilon_1$ is to be determined later. Since $L \log L(\Omega)$ is dense in $L^1(\Omega)$, there exists $g \in L \log L(\Omega)$ such that $\|f - g\|_{L^1(\Omega)} < \epsilon_1$. As

$$\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} g(U_j V_k^k \omega)$$

converges a.e. as was shown by Dunford and Zygmund, we necessarily have

$$\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} g(U_j V_k^k \omega)$$

converges a.e. Hence

$$\mu \left\{ \omega \in \Omega : \left( \limsup_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U_j V_k^k \omega) \right) - \left( \liminf_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U_j V_k^k \omega) \right) > \epsilon \right\}$$

$$= \mu \left\{ \omega \in \Omega : \left( \limsup_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} (f - g)(U_j V_k^k \omega) \right) > \epsilon \right\}$$

$$< C \epsilon \left\| f - g \right\|_{L^1(\Omega)} < \frac{C \epsilon_1}{\epsilon}.$$  

As $\epsilon_1$ is arbitrarily small, the desired result holds. \qed

We remark that an alternative proof of this result may be obtained using techniques of A. Zygmund in [13]. In this paper Zygmund states, without providing details, a result that encompasses the above theorem even in the case of noncommuting measure preserving transformations. However, the transference methods we have constructed in our proof are effectively “reversible” and enable us in the next section to show that certain weak-type bounds on multiparameter ergodic maximal operators are indeed sharp.

3. Nonmonotonic approach regions

In this section we shall show that if the approach region $\Gamma$ is not monotonic, then the weak type $(L \log L, L^1)$ estimate on $M_\Gamma$ is sharp and moreover that the rare ergodic averages associated to $\Gamma$ will converge a.e. for all functions in $L \log L(\Omega)$ but not for all functions in any larger Orlicz class. Observe that the weak type $(L \log L, L^1)$ estimate on $M_\Gamma$ follows from bounding $M_\Gamma$ by the strong ergodic maximal operator $M_S$ and applying De Guzmán’s $(L \log L, L^1)$ estimate for $M_S$. That the rare ergodic averages associated to $\Gamma$ converge for all functions in $L \log L(\Omega)$ follows immediately from Dunford
and Zygmund’s result that the strong ergodic averages of any function in $L \log L(\Omega)$ converge a.e.

Analogous sharpness results for $(L \log L, L^1)$ bounds have been found previously for geometric maximal operators by the second author (see in particular [12].) The strategy here will be to “transfer” the associated techniques of proof used by Stokolos to the ergodic setting, and the means of transferrence will be the Katznelson–Weiss lemma.

Let $I$ and $I'$ be two rectangles in the plane whose sides are parallel to the coordinate axes. If there exists a translation placing one of them inside the other, we say $I$ and $I'$ are comparable. If such a translation does not exist we say $I$ and $I'$ are incomparable.

**Lemma 3.** Let $I_1, \ldots, I_k$ be pairwise incomparable rectangles in the plane whose sides are parallel to the axes and whose sidelengths are dyadic. Then there are two sets $\Theta$ and $Y$ in the plane such that

$$|Y| \geq k2^{k-3}|\Theta|$$

and such that for every $(x, y) \in Y$ there is a shift $\tau$ such that for some $j$,

$$(x, y) \in \tau(I_j) \quad \text{and} \quad |\tau(I_j) \cap \Theta| \geq 2^{1-k}|\tau(I_j)|. $$

Moreover, each $\tau(I_j)$ is a dyadic rectangle, $\Theta \subset Y$, and $Y$ is contained in a dyadic rectangle $H_{\Theta,Y}$ such that

$$\frac{|Y|}{|H_{\Theta,Y}|} \geq k2^{-k-1}. $$

**Proof.** Without loss of generality we assume that $I_1, \ldots, I_k$ have a common lower left vertex. Let $I_j = I_j^1 \times I_j^2$, with $|I_j^1| = 2^{-m_j}$ and $|I_j^2| = 2^{-n_j}$.

We also assume without loss of generality that $I_1^1 \subset I_2^1 \subset \cdots \subset I_k^1$ while $I_1^2 \supset I_2^2 \supset \cdots \supset I_k^2$, corresponding to $m_1 > m_2 > \cdots > m_k$ and $n_1 < n_2 < \cdots < n_k$.

We define $\Theta^1$ and $\Theta^2$ by

$$\Theta^1 = \left\{ x_1 \in I_k^1 : \prod_{j=1}^{k-1} \sum_{s=0}^{2^{m_j}-m_k-1-1} \chi_{I_j^1}(x_1 - 2s |I_j^1|) = 1 \right\}, $$

$$\Theta^2 = \left\{ x_2 \in I_k^2 : \prod_{j=2}^k \sum_{s=0}^{2^{n_j}-n_1-1-1} \chi_{I_j^2}(x_2 - 2s |I_j^2|) = 1 \right\}. $$

Observe that $|\Theta^1| = 2^{1-k} |I_k^1|$ and $|\Theta^2| = 2^{1-k} |I_k^2|$. Set $\Theta = \Theta^1 \times \Theta^2$. Then

$$|\Theta| = 2^{2-2k} |I_k^1| \cdot |I_k^2|. $$

Set now $Y_k^1 = I_k^1$, $Y_k^2 = I_k^2$, and

$$Y_i^1 = \left\{ x_1 \in I_k^1 : \prod_{j=i}^{k-1} \sum_{s=0}^{2^{m_j}-m_k-1-1} \chi_{I_j^1}(x_1 - 2s |I_j^1|) \right\}, $$
for $i = 1, \ldots, k-1$ and $i = 2, \ldots, k$ respectively. We let $Y_i = Y_1^i \times Y_2^i$. Note that $|Y_1^i| = 2^{-(k-i)} |I_k^1|$ and $|Y_2^i| = 2^{1-i} |I_k^2|$. So $|Y_i| = 2^{1-k} |I_k^1| \cdot |I_k^2|$.

Let now $Y = Y_1 \cup \cdots \cup Y_k$. For $j = 1, \ldots, k$, $Y_j$ is a disjoint union of translates of $I_j$, with at least one-quarter of each translate not intersecting any of the other $Y_i$’s. So

$$|Y| \geq \frac{1}{4} \sum_{i=1}^k |Y_i| = k2^{-1-k} |I_k^1| \cdot |I_k^2| = k2^{k-3} |\Theta|.$$  

Moreover, if $(x, y) \in Y$, then $(x, y) \in \tau(I_j)$ for some $1 \leq j \leq k$ and shift $\tau$, where

$$\frac{|\tau(I_j) \cap \Theta|}{|\tau(I_j)|} = \frac{|I_j \cap \Theta|}{|I_j|} = \frac{|Y_j \cap \Theta|}{|Y_j|} = \frac{|\Theta|}{|Y_j|} = \frac{2^{2-2k} |I_k^1| \cdot |I_k^2|}{2^{1-k} |I_k^1| \cdot |I_k^2|} = 2^{1-k}.$$  

Let now $H_{\Theta,Y} = I_k^1 \times I_k^2$. By construction $\Theta \subset Y \subset H_{\Theta,Y}$. Moreover,

$$\frac{|Y|}{|H_{\Theta,Y}|} \geq \frac{k2^{k-3} |\Theta|}{|I_k^1 \times I_k^2|} = \frac{k2^{k-3} 2^{2-2k} |I_k^1| \cdot |I_k^2|}{|I_k^1| \cdot |I_k^2|} = k2^{-k-1},$$  

completing the proof of the lemma. □

Figures 1 and 2 should aid the understanding of the proof of the above lemma. Figure 1 illustrates three incomparable rectangles $I_1$, $I_2$, and $I_3$. Figure 2 features the set $\Theta$ (what is shaded in black) as well as the corresponding $Y$ (the union of the rectangles in the figure).

We now introduce some new notation that will be helpful to us. Given an approach region $\Gamma \subset \mathbb{Z}_+^2$, associate to the dyadic skeleton $\Gamma^*$ of $\Gamma$ the collection of dyadic rectangles $\mathcal{R}_{\Gamma^*}$, where

$$\mathcal{R}_{\Gamma^*} = \left\{ \left[0, 2^m \right] \times \left[0, 2^n \right] : \left(2^m, 2^n \right) \in \Gamma^* \right\}.$$
A crucial observation at this point is that, if $\Gamma$ is not contained in a finite number of monotonic sets, given any positive integer $k$ and positive number $\alpha$ there exists a collection of $k$ pairwise incomparable rectangles in $R_{\Gamma^*}$ all of whose sidelengths exceed $\alpha$.

Given $\Gamma \subset \mathbb{Z}_2^2$ and the associated collection of rectangles $R_{\Gamma^*}$, we now let $\tilde{R}_{\Gamma^*}$ be the collection of dyadic rectangles in the plane consisting of all the shifts of members of $R_{\Gamma^*}$. We define the associated maximal operator $\tilde{M}_{\Gamma^*}$ by

$$\tilde{M}_{\Gamma^*} f(x,y) = \sup_{(x,y) \in \tilde{R}_{\Gamma^*}} \frac{1}{|R|} \int_R |f|.$$  

**Lemma 4.** Suppose $\Gamma \subset \mathbb{Z}_2^2$ is not contained in a finite number of monotonic sets. Let $\epsilon > 0$. For $0 < \lambda < \frac{1}{100}$, let $k \in \mathbb{Z}$ be such that $2^{-k} \leq \lambda < 2^{1-k}$. Then there exist sets $\Theta_{\lambda,\epsilon} \subset Y_{\lambda,\epsilon} \subset H_{\lambda,\epsilon}$ in the plane, all being unions of dyadic squares of sidelength 1 and such that $H_{\lambda,\epsilon}$ is a dyadic square itself, such that

$$\tilde{M}_{\Gamma^*} \chi_{\Theta_{\lambda,\epsilon}} > \lambda \text{ on } Y_{\lambda,\epsilon},$$

$$|Y_{\lambda,\epsilon}| \geq k 2^{k-3} |\Theta_{\lambda,\epsilon}|,$$

and

$$\frac{|H_{\lambda,\epsilon} - Y_{\lambda,\epsilon}|}{|H_{\lambda,\epsilon}|} < \epsilon.$$

**Proof.** Since $\Gamma$ is not contained in a finite number of monotonic sets, there exist a collection $I_{1,1}, \ldots, I_{1,k}$ of pairwise incomparable rectangles in $R_{\Gamma^*}$. By the previous lemma, there are two sets $\tilde{\Theta}_1$ and $\tilde{Y}_1$ in the plane such that

$$|\tilde{Y}_1| \geq k 2^{k-3} |\tilde{\Theta}_1|$$

and such that for every $(x,y) \in \tilde{Y}_1$ there is a shift $\tau$ such that for some $j$,

$$(x,y) \in \tau (I_{1,j}) \text{ and } |\tau (I_{1,j}) \cap \tilde{\Theta}_1| \geq 2^{1-k} |\tau (I_{1,j})|.$$
Moreover, each \( \tau(I_{1,j}) \) is a dyadic rectangle and \( \tilde{\Theta}_1 \) and \( \tilde{Y}_1 \) lie in a dyadic rectangle \( H_1 \) such that
\[
\frac{|\tilde{Y}_1|}{|H_1|} \geq k2^{1-k}.
\]
Observe that \( \tilde{M}_{\Gamma} \cdot \chi_{\tilde{\Theta}_1} > 2^{1-k} \) on \( \tilde{Y}_1 \).

Let now \( I_{2,1}, \ldots, I_{2,k} \) be a collection of pairwise incomparable rectangles in \( \mathcal{R}_\Gamma \) all of whose sidelengths exceed the longest sidelength of \( H_1 \). Applying the previous lemma again we obtain two sets \( \Theta_2 \) and \( Y_2 \) in the plane such that
\[
|Y_2| \geq k2^{k-3} |\Theta_2|
\]
and such that for every \((x,y) \in Y_2\) there is a shift \( \tau \) such that for some \( j \),
\[(x,y) \in \tau(I_{2,j}) \text{ and } |\tau(I_{2,j}) \cap \Theta_2| \geq 2^{1-k} |\tau(I_{2,j})|.
\]
Moreover, each \( \tau(I_{2,j}) \) is a dyadic rectangle, \( \Theta_2 \subset Y_2 \), and \( Y_2 \) lies in a dyadic rectangle \( H_2 \) such that
\[
\frac{|Y_2|}{|H_2|} \geq k2^{1-k}.
\]

Assuming without loss of generality that the construction of \( \Theta_2 \) and \( Y_2 \) from the \( I_{2,j} \) was like the one described in the proof of the previous lemma, \( H_2 - Y_2 \) consists of an a.e. disjoint union of dyadic rectangles, each being a translate of \( H_1 \). (This follows from the method of construction and the fact that each \( I_{2,j} \) has sidelengths exceeding the largest sidelength of \( H_1 \).) Defining the shift operators \( \tau_{2,1}, \ldots, \tau_{2,\ell_2} \) such that \( H_2 - Y_2 \) is the a.e. disjoint union of the \( \tau_{2,j}H_1 \), we set
\[
\tilde{Y}_2 = Y_2 \cup \left( \bigcup_{j=1}^{\ell_2} \tau_{2,j}\tilde{Y}_1 \right),
\]
\[
\tilde{\Theta}_2 = \Theta_2 \cup \left( \bigcup_{j=1}^{\ell_2} \tau_{2,j}\tilde{\Theta}_1 \right).
\]

An important observation here is that
\[
\frac{|H_2 - \tilde{Y}_2|}{|H_2|} \leq \left( 1 - k^{-1-k} \right)^2
\]
and
\[
|\tilde{Y}_2| \geq k2^{k-3} |\tilde{\Theta}_2|.
\]

Also note that \( \tilde{M}_{\Gamma} \cdot \chi_{\tilde{\Theta}_2} > \lambda \) on \( \tilde{Y}_2 \).

We proceed by induction. Suppose \( \tilde{Y}_n, \tilde{\Theta}_n, \text{ and } H_n \) have been constructed, all being unions of rectangles in \( \tilde{R}_\Gamma \). Moreover, suppose \( \tilde{M}_{\Gamma} \cdot \chi_{\tilde{\Theta}_n} > \lambda \) on \( \tilde{Y}_n \),
and

\[ \frac{|H_n - \tilde{Y}_n|}{|H_n|} \leq (1 - k^{-1-k})^n. \]

Let \( I_{n+1,1}, \ldots, I_{n+1,k} \) be a collection of incomparable rectangles in \( \mathcal{R}_\Gamma \) all of whose sidelengths exceed the longest sidelength of \( H_n \). Applying the techniques of the previous lemma we obtain two sets \( \Theta_{n+1}, Y_{n+1} \) in the plane such that

\[ |Y_{n+1}| \geq k^{2^{k-3}} |\Theta_{n+1}| \]

and such that for every \((x, y) \in Y_{n+1}\) there is a shift \( \tau \) such that for some \( j \), \((x, y) \in \tau(I_{n+1,j}) \) and \( |\tau(I_{n+1,j}) \cap \Theta_{n+1}| \geq 2^{1-k} |\tau(I_{n+1,j})| \). Moreover, each \( \tau(I_{n+1,j}) \) is a dyadic rectangle, \( \Theta_{n+1} \subseteq Y_{n+1} \), and \( \Theta_{n+1} \) and \( Y_{n+1} \) lie in a dyadic rectangle \( H_{n+1} \) such that \( |Y_{n+1}| |H_{n+1}| \geq k^{2^{k-1}-k} \).

Now, \( H_{n+1} - Y_{n+1} \) is an a.e. disjoint union of dyadic rectangles each being a translate of \( H_n \), due to the nature of construction of \( \Theta_{n+1} \) and \( Y_{n+1} \) and the fact that each \( I_{n+1,j} \) has sidelengths exceeding the largest sidelength of \( H_n \). Defining \( \tau_{n+1,1}, \ldots, \tau_{n+1,\ell_{n+1}} \) such that \( H_{n+1} - Y_{n+1} \) is an a.e. disjoint union of the \( \tau_{n+1,j}H_n \), we set

\[ \tilde{Y}_{n+1} = Y_{n+1} \cup \left( \bigcup_{j=1}^{\ell_{n+1}} \tau_{n+1,j} \tilde{Y}_n \right) \]

and

\[ \tilde{\Theta}_{n+1} = \Theta_{n+1} \cup \left( \bigcup_{j=1}^{\ell_{n+1}} \tau_{n+1,j} \tilde{\Theta}_n \right). \]

Note that

\[ \frac{|H_{n+1} - \tilde{Y}_{n+1}|}{|H_{n+1}|} \leq (1 - k^{-1-k})^{n+1}, \]

\[ \tilde{M}_\Gamma \chi_{\tilde{\Theta}_{n+1}} > \lambda \text{ on } \tilde{Y}_{n+1}, \]

and

\[ |\tilde{Y}_{n+1}| \geq k^{2^{k-3}} |\tilde{\Theta}_{n+1}|. \]

Let now \( N = N(\lambda, \epsilon) \in \mathbb{Z}^+ \) be such that \((1 - k^{-1-k})^N < \epsilon\). \( H_N \) is not necessarily a dyadic square. However, there exist a collection of shift operators \( \tau_{H_N,j} \) for \( 1 \leq j \leq r_{H_N} \) such that the a.e. disjoint union of the \( \tau_{H_N,j} \) forms a dyadic square. Defining \( \Theta_{\lambda,\epsilon}, Y_{\lambda,\epsilon}, \) and \( H_{\lambda,\epsilon} \) by

\[ \Theta_{\lambda,\epsilon} = \bigcup_{j=1}^{r_{H_N}} \tau_{H_N,j}(\Theta_N), \]

\[ Y_{\lambda,\epsilon} = \bigcup_{j=1}^{r_{H_N}} \tau_{H_N,j}(Y_N), \]
and
\[ H_{\lambda,\epsilon} = \bigcup_{j=1}^{r_{HN}} \tau_{H,j}(H_N), \]
we obtain the lemma. □

We now consider some pleasantries associated to the fact that, although \( M_\Gamma \) is a “centered” maximal operator, \( \tilde{M}_\Gamma \) is not. We define the four “quasi-centered” maximal operators \( \tilde{M}_{\Gamma^*,I}, \tilde{M}_{\Gamma^*,II}, \tilde{M}_{\Gamma^*,III}, \) and \( \tilde{M}_{\Gamma^*,IV} \) by
\[
\tilde{M}_{\Gamma^*,I}f(x,y) = \sup_{R \in R_{\Gamma^*}} \frac{1}{|R|} \int_R f([x],[y]) + (u,v) \, dudv ,
\]
\[
\tilde{M}_{\Gamma^*,II}f(x,y) = \sup_{R \in R_{\Gamma^*}} \frac{1}{|R|} \int_R f([x],[y]) + (-u,v) \, dudv ,
\]
\[
\tilde{M}_{\Gamma^*,III}f(x,y) = \sup_{R \in R_{\Gamma^*}} \frac{1}{|R|} \int_R f([x],[y]) + (-u,-v) \, dudv ,
\]
and
\[
\tilde{M}_{\Gamma^*,IV}f(x,y) = \sup_{R \in R_{\Gamma^*}} \frac{1}{|R|} \int_R f([x],[y]) + (u,-v) \, dudv .
\]
Note that \( \tilde{M}_{\Gamma^*}f \leq \tilde{M}_{\Gamma^*,I}f + \tilde{M}_{\Gamma^*,II}f + \tilde{M}_{\Gamma^*,III}f + \tilde{M}_{\Gamma^*,IV}f \). We may assume without loss of generality that on a set within \( Y_{\lambda,\epsilon} \) of measure at least \( \frac{1}{4} |Y_{\lambda,\epsilon}| \) that \( \tilde{M}_{\Gamma^*,I} \chi_{\Theta_{\lambda,\epsilon}} \geq \frac{1}{4} \tilde{M}_{\Gamma^*} \chi_{\Theta_{\lambda,\epsilon}} \). To see this, suppose it had been that, say, \( \tilde{M}_{\Gamma^*,II} \chi_{\Theta_{\lambda,\epsilon}} \geq \frac{1}{4} \tilde{M}_{\Gamma^*} \chi_{\Theta_{\lambda,\epsilon}} \) on a set within \( Y_{\lambda,\epsilon} \) of measure at least \( \frac{1}{4} |Y_{\lambda,\epsilon}| \). Assuming without loss of generality that \( H_{\lambda,\epsilon} \) were situated such that its lower left hand corner were at the origin, we could replace \( \Theta_{\lambda,\epsilon}, Y_{\lambda,\epsilon} \) by sets \( \Theta'_{\lambda,\epsilon} \) and \( Y'_{\lambda,\epsilon} \), where
\[
\chi_{\Theta'_{\lambda,\epsilon}}(x,y) = \chi_{\Theta_{\lambda,\epsilon}}(|H_{\lambda,\epsilon}|^{1/2} - x,y) ,
\]
\[
\chi_{Y'_{\lambda,\epsilon}}(x,y) = \chi_{Y_{\lambda,\epsilon}}(|H_{\lambda,\epsilon}|^{1/2} - x,y) .
\]
Observe that \( \tilde{M}_{\Gamma^*,II} \chi_{\Theta_{\lambda,\epsilon}} \geq \frac{1}{4} \tilde{M}_{\Gamma^*} \chi_{\Theta_{\lambda,\epsilon}} \) on a set of measure at least \( \frac{1}{4} |Y_{\lambda,\epsilon}| \) implies that \( \tilde{M}_{\Gamma^*,I} \chi_{\Theta'_{\lambda,\epsilon}} \geq \frac{1}{4} \tilde{M}_{\Gamma^*} \chi_{\Theta'_{\lambda,\epsilon}} \) on a set of measure at least \( \frac{1}{4} |Y_{\lambda,\epsilon}| \). Relabeling \( \Theta'_{\lambda,\epsilon} \) and \( Y'_{\lambda,\epsilon} \) by \( \Theta_{\lambda,\epsilon} \) and \( Y_{\lambda,\epsilon} \) we would obtain the desired result. Similar symmetries apply if we replace \( \tilde{M}_{\Gamma^*,II} \) by \( \tilde{M}_{\Gamma^*,III} \) or \( \tilde{M}_{\Gamma^*,IV} \).

We summarize these considerations with the following.

**Lemma 5.** Suppose \( \Gamma \subset \mathbb{Z}_2^2 \) is not contained in a finite number of monotonic sets. Let \( \epsilon > 0 \). For \( 0 < \lambda < \frac{1}{100} \), let \( k \in \mathbb{Z} \) be such that \( 2^{-k} \leq \lambda < 2^{1-k} \). Then there exist sets \( \Theta_{\lambda,\epsilon} \subset Y_{\lambda,\epsilon} \subset H_{\lambda,\epsilon} \) in the plane, all being unions of dyadic squares of sidelength 1 and such that \( H_{\lambda,\epsilon} \) is a dyadic square itself, such that
\[
\tilde{M}_{\Gamma^*,I} \chi_{\Theta_{\lambda,\epsilon}}(x,y) > \frac{1}{4} \lambda \text{ for any } (x,y) \in Y_{\lambda,\epsilon} ,
\]
\[ |Y_{\lambda, \epsilon}| \geq \frac{1}{4} k 2^{k-3} |\Theta_{\lambda, \epsilon}|, \]

and

\[ \frac{|H_{\lambda, \epsilon} - Y_{\lambda, \epsilon}|}{|H_{\lambda, \epsilon}|} < \frac{3}{4} + \epsilon. \]

By means of transference we now obtain an ergodic analogue of Lemma 5.

**Lemma 6.** Let \( U \) and \( V \) be two commuting nonperiodic measure preserving transformations on a probability space \((\Omega, \Sigma, \mu)\), and suppose \( \Gamma \subset \mathbb{Z}^2_+ \) is not contained in a finite union of monotonic sets. Let \( 0 < \lambda < \frac{1}{100}, 0 < \epsilon < 1 \).

Then there exists a set \( A_{\lambda, \epsilon} \subset \Omega \) such that:

(i) \( M_{\Gamma^* \chi_{A_{\lambda, \epsilon}}} \geq \frac{1}{4} \lambda \) on \( \Omega \) on a set of measure greater than \( \frac{1}{4} - 2 \epsilon \), and

(ii) \( |A_{\lambda, \epsilon}| \leq \frac{100 \lambda}{\log(\frac{1}{\lambda})} \).

**Proof.** Let \( k \in \mathbb{Z} \) be such that \( 2^{-k} \leq \lambda < 2^{1-k} \) and let \( \Theta_{\lambda, \epsilon}, Y_{\lambda, \epsilon}, \) and \( H_{\lambda, \epsilon} \) be as is provided by Lemma 5. For notational convenience let \( \rho_{\lambda, \epsilon} = |H_{\lambda, \epsilon}|^{1/2} \). Applying the Katznelson–Weiss lemma (Lemma 2) we obtain sets \( B_{\lambda, \epsilon} \) and \( E_{\lambda, \epsilon} \) in \( \Omega \) such that

\[ \Omega = \left( \bigcup_{j,k=0}^{\rho_{\lambda, \epsilon}^{-1}} U^j V^k B_{\lambda, \epsilon} \right) \cup E_{\lambda, \epsilon}, \]

where the \( U^j V^k B_{\lambda, \epsilon} \) are pairwise a.e. disjoint.

Let \( S_{\lambda, \epsilon} = \{(j,k) : (j + \frac{1}{2}, k + \frac{1}{2}) \in \Theta_{\lambda, \epsilon}\} \) and \( A_{\lambda, \epsilon} = \bigcup_{(j,k) \in S_{\lambda, \epsilon}} U^j V^k B_{\lambda, \epsilon} \). Let \( T_{\lambda, \epsilon} = \{(j,k) : (j + \frac{1}{2}, k + \frac{1}{2}) \in Y_{\lambda, \epsilon}\} \) and \( W_{\lambda, \epsilon} = \bigcup_{(j,k) \in T_{\lambda, \epsilon}} U^j V^k B_{\lambda, \epsilon} \). Observe that \( |A_{\lambda, \epsilon}| \leq \frac{|\Theta_{\lambda, \epsilon}|}{|H_{\lambda, \epsilon}|} \) and \( |W_{\lambda, \epsilon}| > (1 - \epsilon) |Y_{\lambda, \epsilon}| \geq \frac{|Y_{\lambda, \epsilon}|}{|H_{\lambda, \epsilon}|} - \epsilon \). By Lemma 5 we then have

\[ |A_{\lambda, \epsilon}| \leq 4k^{-1} 2^{k-3} \leq \frac{100 \lambda}{\log(\frac{1}{\lambda})} \]

and

\[ |W_{\lambda, \epsilon}| > \frac{1}{4} - 2 \epsilon. \]

Note also that, as \( M_{\Gamma^* \chi_{A_{\lambda, \epsilon}}}(x, y) > \frac{1}{4} \lambda \) for any \((x, y) \in Y_{\lambda, \epsilon}\), we must have that \( M_{\Gamma^* \chi_{A_{\lambda, \epsilon}}} > \frac{1}{4} \lambda \) on \( W_{\lambda, \epsilon} \), completing the proof of the lemma. \( \square \)

We now are in position to show that, if the approach region \( \Gamma \subset \mathbb{Z}^2_+ \) is not contained in a finite union of monotonic sets, then \( L \log L(\Omega) \) is the largest Orlicz class of functions for which we have a.e. convergence.

**Theorem 2.** Let \( U \) and \( V \) be a commuting pair of nonperiodic measure preserving transformations on a probability space \((\Omega, \Sigma, \mu)\), and suppose \( \Gamma \subset \mathbb{Z}^2_+ \) is not contained in a finite union of monotonic sets. Let \( \phi \) be a positive
increasing function on \([0, \infty)\) that is \(o(\log x)\) as \(x \to \infty\). Then there exists a function \(f \in L\phi(L)(\Omega)\) such that

\[
\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^j V^k \omega) \neq \infty
\]

does not exist on a set of positive measure in \(\Omega\).

**Proof.** For each positive integer \(n\), choose \(0 < \lambda_n < \frac{1}{100}\) such that

\[
\phi \left( \frac{n}{\lambda_n} \right) < \frac{1}{n \cdot 2^n} \log \left( \frac{1}{\lambda_n} \right) < 1.
\]

Note that such a \(\lambda_n\) exists since \(\phi(x) = o(\log x)\) as \(x \to \infty\). By Lemma 6, there exists a set \(E_n \subset \Omega\) such that \(M_{\Gamma}E_n \geq \frac{1}{16} \lambda_n\) on \(\Omega\) on a set of measure at least \(\frac{1}{8}\), where \(|E_n| \leq \frac{100\lambda_n}{\log(\frac{1}{\lambda_n})}\).

Let now \(f_n = \frac{n}{\lambda_n} \chi_{E_n}\). Note that \(M_{\Gamma} f_n > \frac{n}{16}\) on \(\Omega\) on a set of measure at least \(\frac{1}{8}\). Moreover,

\[
\int_{\Omega} f_n \phi(f_n) = |E_n| \cdot \frac{n}{\lambda_n} \phi \left( \frac{n}{\lambda_n} \right) \\
\leq \frac{100\lambda_n}{\log(\frac{1}{\lambda_n})} \cdot \frac{n}{\lambda_n} \phi \left( \frac{n}{\lambda_n} \right) \\
\leq \frac{n\phi \left( \frac{n}{\lambda_n} \right)}{\log(\frac{1}{\lambda_n})} \\
< \frac{100}{2^n}.
\]

Set now \(f = \sup_n f_n\). Observe that \(M_{\Gamma} f = \infty\) in \(\Omega\) on a set of measure at least \(\frac{1}{8}\) and hence for each \(\omega\) in a set of measure \(\frac{1}{8}\) in \(\Omega\) there exist sequences of positive integers \(j_\omega,1, j_\omega,2, j_\omega,3, \ldots, k_\omega,1, k_\omega,2, k_\omega,3, \ldots\) tending to infinity with each \((j_\omega,n, k_\omega,n) \in \Gamma\) such that

\[
\lim_{n \to \infty} \frac{1}{j_\omega,n k_\omega,n} \sum_{j=0}^{j_\omega,n-1} \sum_{k=0}^{k_\omega,n-1} f(U^j V^k \omega) = \infty.
\]

Moreover, \(f \in L\phi(L)(\Omega)\) since

\[
\sum_{n=1}^{\infty} \int_{\Omega} f_n \phi(f_n) < \sum_{n=1}^{\infty} \frac{100}{2^n} = 100.
\]
As accordingly \( f \in L^1(\Omega) \) we also have
\[
\int \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^j V^k) \leq \|f\|_{L^1(\Omega)}
\]
for all positive integers \( m, n \), and hence it is not possible for
\[
\lim_{m,n \to \infty} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^j V^k) = \infty
\]
to hold for all \( \omega \) in a set in \( \Omega \) of measure \( \frac{1}{8} \) (even though on such a set we may have \( \limsup_{(m,n) \in \Gamma} \frac{1}{mn} \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} f(U^j V^k) = \infty \)). The theorem follows. \( \square \)

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