

LINEAR LAW FOR THE LOGARITHMS OF THE RIEMANN PERIODS AT SIMPLE CRITICAL ZETA ZEROS

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ABSTRACT. Each simple zero $\frac{1}{2} + i\gamma_n$ of the Riemann zeta function on the critical line with $\gamma_n > 0$ is a center for the flow $\dot{s} = \xi(s)$ of the Riemann xi function with an associated period T_n . It is shown that, as $\gamma_n \rightarrow \infty$,

$$\log T_n \geq \frac{\pi}{4}\gamma_n + O(\log \gamma_n).$$

Numerical evaluation leads to the conjecture that this inequality can be replaced by an equality. Assuming the Riemann Hypothesis and a zeta zero separation conjecture $\gamma_{n+1} - \gamma_n \gg \gamma_n^{-\theta}$ for some exponent $\theta > 0$, we obtain the upper bound $\log T_n \ll \gamma_n^{2+\theta}$. Assuming a weakened form of a conjecture of Gonek, giving a bound for the reciprocal of the derivative of zeta at each zero, we obtain the expected upper bound for the periods so, conditionally, $\log T_n = \frac{\pi}{4}\gamma_n + O(\log \gamma_n)$. Indeed, this linear relationship is equivalent to the given weakened conjecture, which implies the zero separation conjecture, provided the exponent is sufficiently large. The frequencies corresponding to the periods relate to natural eigenvalues for the Hilbert–Polya conjecture. They may provide a goal for those seeking a self-adjoint operator related to the Riemann hypothesis.

1. INTRODUCTION

If a holomorphic function of a single complex variable $f(s)$ has a simple zero at s_o which is a center for the dynamical system $\dot{s} = f(s)$, then the period of an orbit encircling s_o is given by $2\pi i/f'(s_o)$ [3, Theorem 2.3], and, in particular, is independent of the orbit. When this is applied to the simple zeros of Riemann's function $\xi(s)$, which lie on the critical line $s = \frac{1}{2}$ and which coincide with the simple critical zeros of $\zeta(s)$, we see that the periods $\{\tau_n = 2\pi i/\xi'(\frac{1}{2} + i\gamma_n) : \xi(\frac{1}{2} + i\gamma_n) = 0\}$ could be of interest since each such (real) number applies to an infinite family of nested orbits. See Figure 1 where selected periodic orbits surrounding the 27th and 28th zeros of zeta for the flow $\dot{s} = \xi(s)$ are displayed.

Even though the positions of the zeros on the critical line have a considerable degree of random variation, the values of the periods are quite constrained, as is illustrated numerically in Figure 2 and partly proved in Theorem 4.1: The logarithm of the absolute value of the periods varies linearly with the position of the zero.

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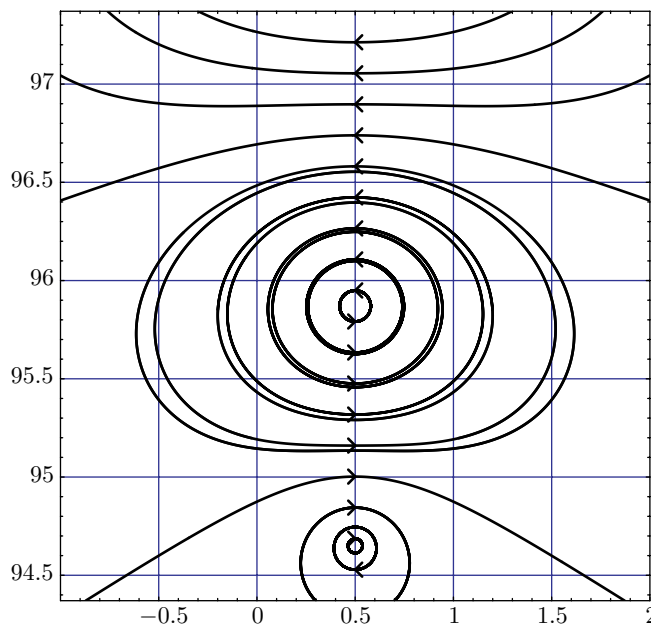


FIGURE 1. Orbits around the 27th and 28th zero for $\dot{z} = \xi(z)$.

In Section 2 the numerical evaluation is developed. Of the 500 zeta zeros studied, being those with smallest positive t coordinates, the periods always increased with increasing zero value, with four exceptions. The numerical evidence demonstrates a relationship between each period and the t -coordinate of the corresponding zero which is very close to being linear.

In Section 3 some preliminary lemmas are given.

In Section 4 the relationship

$$\log T_n \geq \frac{\pi}{4}\gamma_n + O(\log \gamma_n),$$

where $T_n = (-1)^n \tau_n$ is the absolute value of the period, is proved. An upper bound is derived subject to the Riemann Hypothesis and a plausible conjecture on zero separations. Using a weakened form of a conjecture of Gonek (which includes the Riemann Hypothesis), namely, that there exists a nonnegative real number θ such that $|\zeta'(\frac{1}{2} + i\gamma_n)|^{-1} = O(|\gamma_n|^\theta)$ for all $n \in \mathbb{N}$, we derive the precise upper bound and hence, conditionally,

$$\log T_n = \frac{\pi}{4}\gamma_n + O(\log \gamma_n).$$

In Section 5 a possible significance of the periods, in the context of the Hilbert–Polya conjecture, is sketched.

We first define some notations. Let $s = \sigma + it$, $\xi(s) = u(\sigma, t) + iv(\sigma, t)$. Label the simple zeros of $\xi(s)$, with a positive t coordinate, going up the critical line as $\{\gamma_n : n \in \mathbb{N}\}$. A particular zero $\frac{1}{2} + i\gamma_n$ has the corresponding period

$$\tau_n = \frac{2\pi i}{\xi'(\frac{1}{2} + i\gamma_n)}.$$

Because $\xi(s)$ is real on the critical line, $v_t(\frac{1}{2}, t) = 0$, so $\xi'(\frac{1}{2} + it) = -iu_t(\frac{1}{2}, t)$. Therefore $T_n = 2\pi/|u_t(\frac{1}{2}, \gamma_n)|$.

Let $s = \frac{1}{2} + it$ and write the ξ definition from Section 2 as

$$\begin{aligned} \xi(\frac{1}{2} + it) &= e^{\log \Gamma(\frac{s}{2})} \pi^{-s/2} \frac{s(s-1)}{2} \zeta(s) \\ &= -e^{\Re \log \Gamma(\frac{s}{2})} \pi^{-1/4} \left(\frac{t^2 + 1/4}{2}\right) \times Z(t) \\ &= Y(t) \times Z(t), \end{aligned}$$

where

$$\begin{aligned} \log \Gamma(s + 1) &= (s + \frac{1}{2}) \log s - s + c_1 + O(\frac{1}{s}) \\ Z(t) &= e^{i\vartheta(t)} \zeta(\frac{1}{2} + it) \\ \vartheta(t) &= \frac{t}{2} \log\left(\frac{t}{2\pi}\right) - \frac{t}{2} - \frac{\pi}{8} + O\left(\frac{1}{t}\right), \end{aligned}$$

and where here and in what follows the c_1, c_2, \dots are absolute constants.

2. NUMERICAL EVALUATION OF THE PERIODS

We used the Chebyshev method of P. Borwein [2] to evaluate $\zeta(s)$. Our version is described in [3, section 5] in which accuracies for the ζ -zeros $\gamma_1 - \gamma_{502}$ better than 10^{-10} were demonstrated.

A program was written in MATLAB using the methods of Godfrey [10] for both the ζ -function and the complex Γ -function. They are available in Godfrey's MATLAB site as part of the zeta-function code. In particular, values of the gamma

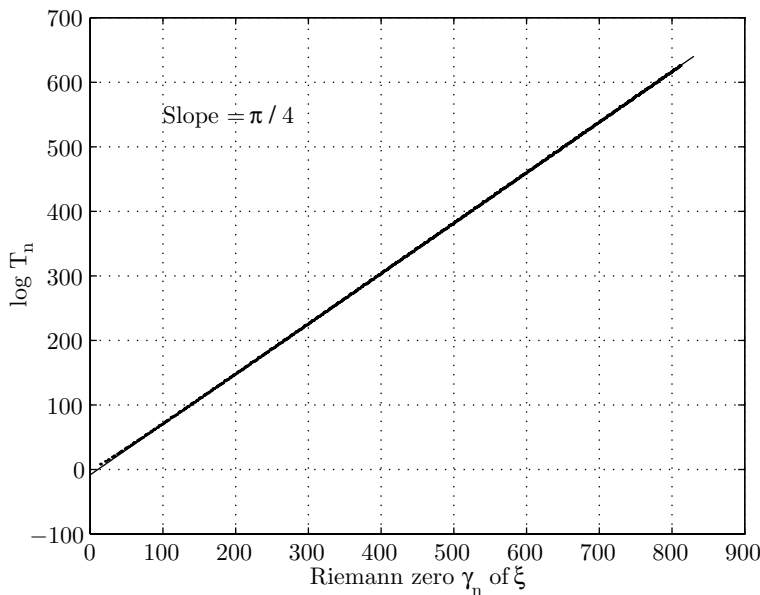


FIGURE 2. Plot of logarithm of the period magnitudes against the Riemann zeros up to $\gamma_{502} = 814.1 \dots$.

TABLE 1. Numerical values of the first 20 γ_n -values and logarithms of the periods.

n	γ_n	$\log T_n$	T_n
1	14.13473	8.4242	4.5562e+003
2	21.02204	12.7793	3.5480e+005
3	25.01086	15.4167	4.9589e+006
4	30.42488	19.3796	2.6089e+008
5	32.93506	21.1554	1.5406e+009
6	37.58618	24.2391	3.3645e+010
7	40.91872	26.9664	5.1445e+011
8	43.32707	28.5531	2.5145e+012
9	48.00515	32.2017	9.6613e+013
10	49.77383	33.6324	4.0399e+014
11	52.97032	35.4970	2.6071e+015
12	56.44625	38.1368	3.6525e+016
13	59.34704	40.8634	5.5814e+017
14	60.83178	41.8135	1.4434e+018
15	65.11254	44.7276	2.6604e+019
16	67.07981	46.4654	1.5124e+020
17	69.54640	48.1391	8.0639e+020
18	72.06716	49.7490	4.0339e+021
19	75.70469	53.0341	1.0775e+023
20	77.14484	54.3339	3.9529e+023

function needed for the definition

$$\xi(s) = \frac{s}{2}(s-1)\Gamma\left(\frac{s}{2}\right)\pi^{-s/2}\zeta(s),$$

TABLE 2. Numerical values of the logarithms of the periods and γ_n -values showing the four anomalous, decreasing periods as n increases.

n	γ_n	$\log T_n$	T_n
299	540.63139	415.2032	2.0914e+180
300	541.84744	414.7731	1.3605e+180
301	544.32389	416.2643	6.0437e+180
364	630.80578	485.7808	9.3738e+210
365	632.22514	485.6408	8.1491e+210
366	633.54686	486.1135	1.3075e+211
446	740.57381	571.0652	1.0244e+248
447	741.75734	571.0002	9.5995e+247
448	743.89501	572.2458	3.3357e+248
481	786.46115	606.9047	3.7614e+263
482	787.46846	606.8254	3.4747e+263
483	790.05909	608.9406	2.8810e+264

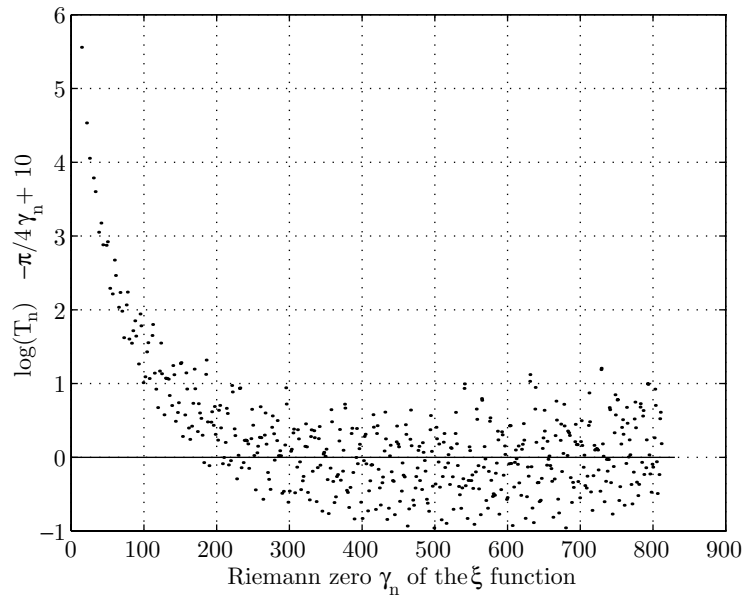


FIGURE 3. The residuals using a slope of $\pi/4$.

do not have to be incorporated into a Riemann–Siegel formulation. The values $\xi'(\frac{1}{2} + i\gamma_n)$ were found by differencing. Figure 2 gives an illustration of the linear relation of this paper for zeros up to $t = \gamma_{502} = 814.1\dots$.

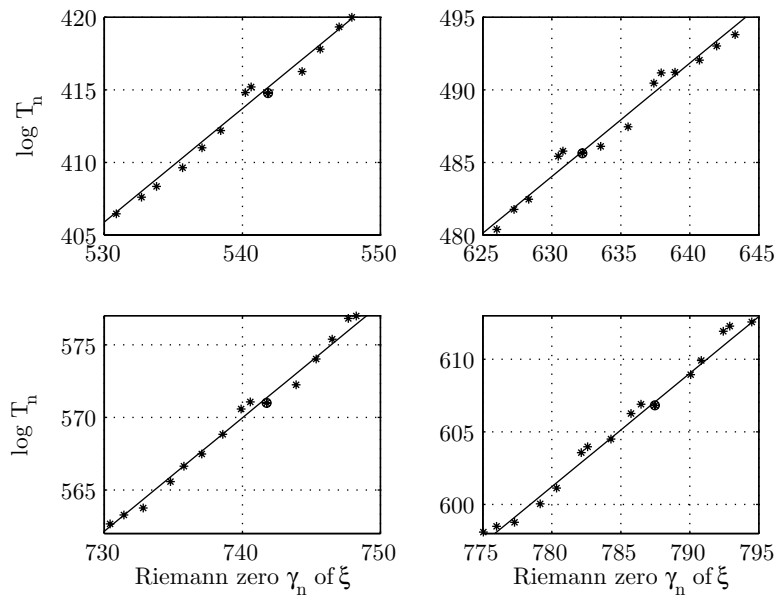


FIGURE 4. The first four anomalous deviations from monotonicity (circled).

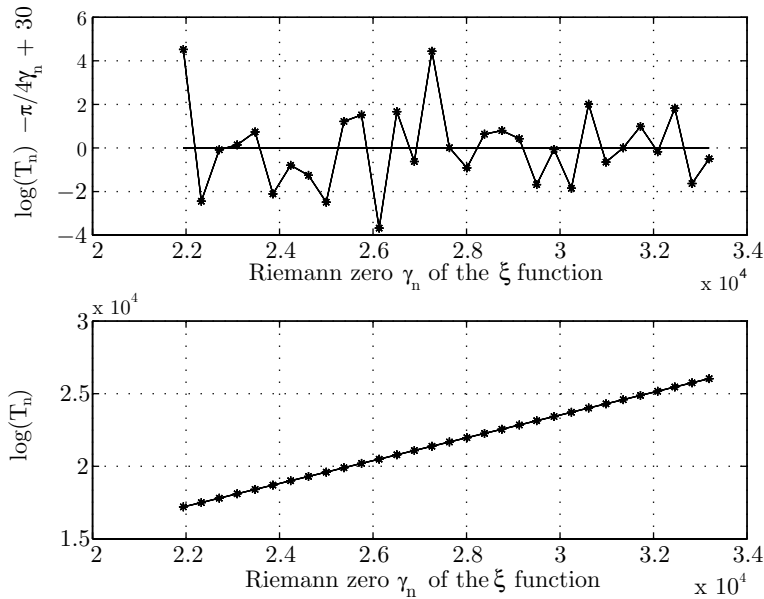


FIGURE 5. The linear periods (below) and residuals (above) using a slope of $\pi/4$.

Figure 3 shows the deviations from the linear law $\log T_n = \alpha + \frac{\pi}{4}\gamma_n$. There is a rise, matching an exponential, at low γ -values. The value of α for the fit is -10.0 .

Table 1 shows the zeros and periods for $0 < n \leq 20$, where the slope deviates slightly from $\pi/4$, as is seen in Figure 3. The *rms* deviation for the complete fit is 1.5.

Table 2 includes the zeros and periods for $\gamma_{300} = 541.847 \dots$, $\gamma_{365} = 632.225 \dots$, $\gamma_{447} = 741.757 \dots$, and $\gamma_{482} = 787.468 \dots$, where, anomalously, we find $\log T_n < \log T_{n-1}$ which are the only examples below γ_{502} where the period decreases. These are plotted with an expanded scale in Figure 4. An alternative calculation was devised to extend the modest upper value of $t \sim 800$ to $t \sim 34000$. The same linear relationship was found to hold. The symbolic ζ -calculations of MapleTM were combined with Godfrey’s implementation of Lanczos’ Γ -function method. Earlier values $t \leq 814.1 \dots$ were confirmed. The results are presented in increments of 500 in Figure 5.

3. PRELIMINARY LEMMAS

Lemma 3.1. *As $t \rightarrow \infty$*

$$\Re \log \Gamma\left(\frac{1}{2} + it\right) = -\frac{1}{8} \log(9 + 4t^2) - \frac{\pi}{4}t + c_2 + O\left(\frac{1}{t}\right).$$

Proof. This follows directly from Stirling’s approximation given in Section 1 above. □

Lemma 3.2. *As $t \rightarrow \infty$, $|\vartheta'(t)| = O(\log t)$.*

Proof. This follows directly from the expression for $\vartheta(t)$ given above or see [8, Page 125]. □

Lemma 3.3. As $t \rightarrow \infty$, $|\zeta(\frac{1}{2} + it)| = O(t^{1/6} \log^{3/2} t)$.

Proof. This is [17, Page 99]. □

Lemma 3.4. As $t \rightarrow \infty$,

$$\begin{aligned} |\zeta'(\frac{1}{2} + it)| &= O(t^{1/4} \log^2 t) \\ \text{and } |\zeta''(\frac{1}{2} + it)| &= O(t^{1/4} \log^4 t). \end{aligned}$$

Proof. These bounds follow from the upper bound for $\zeta^{(k)}(\frac{1}{2} + it)$, derived using the approximate functional equation and Cauchy's integral formula for the n th derivative given in [13, Page 57], namely,

$$\begin{aligned} |\zeta^{(k)}(\frac{1}{2} + it)| \leq & \left| \sum_{n \leq \sqrt{t/2\pi}} \frac{\log^k n}{n^{1/2+it}} \right| + \log^k t \sum_{1 \leq j \leq k} \left| \sum_{n \leq \sqrt{t/2\pi}} \frac{\log^j n}{n^{1/2-it}} \right| \\ & + O(t^{-1/4} \log^k t). \end{aligned} \quad \square$$

Lemma 3.5. As $t \rightarrow \infty$, $Z'(t) = O(t^{1/4} \log^2 t)$.

Proof. This follows directly from $Z(t) = e^{i\theta(t)}\zeta(\frac{1}{2} + it)$ after differentiating and using Lemmas 3.2 and 3.4. □

4. LOWER AND UPPER BOUNDS FOR THE LINEAR RELATIONSHIP

Theorem 4.1. For $n \in \mathbb{N}$,

$$\log T_n \geq \frac{\pi}{4} \gamma_n + O(\log \gamma_n).$$

Proof. We first have

$$|u_t(\frac{1}{2}, t)| = |\xi'(\frac{1}{2} + it)|$$

and

$$i\xi'(\frac{1}{2} + it) = Y'(t)Z(t) + Y(t)Z'(t).$$

Since $Z(\gamma_n) = 0$,

$$|\xi'(\frac{1}{2} + i\gamma_n)| = |Y(\gamma_n)| \times |Z'(\gamma_n)|.$$

So

$$\log |u_t(\frac{1}{2}, \gamma_n)| = \log |Y(\gamma_n)| + \log |Z'(\gamma_n)|.$$

By Lemma 3.1,

$$\begin{aligned} \log |Y(t)| &= \Re \log \Gamma\left(\frac{1}{2} + it\right) - \frac{1}{4} \log \pi + \log\left(\frac{1}{8} + \frac{t^2}{2}\right) \\ &= -\frac{\pi}{4}t + \log\left(\frac{1 + 4t^2}{(9 + 4t^2)^{1/8}}\right) + c_3 + O\left(\frac{1}{t}\right). \end{aligned}$$

Therefore, by Lemma 3.5,

$$\log |u_t(\frac{1}{2}, \gamma_n)| \leq -\frac{\pi}{4} \gamma_n + O(\log \gamma_n),$$

and therefore

$$\log T_n \geq \frac{\pi}{4} \gamma_n + O(\log \gamma_n). \quad \square$$

Finding upper bounds for the periods appears to be a much more difficult problem. Assuming the Riemann Hypothesis (RH) and a plausible zero separation hypothesis, we make some progress on this issue. Later we show how the upper bound follows (indeed is equivalent to) a weakened form of a conjecture of Gonek.

Fujii [9] has shown that there exists a $\lambda > 1$ such that for n in a set of positive density

$$\frac{\gamma_{n+1} - \gamma_n}{2\pi / \log \gamma_n} \geq \lambda.$$

Since [17, Page 214] $\gamma_n \sim 2\pi n / \log n$, Fujii’s result implies for all $\epsilon > 0$ and n sufficiently large and in a subset of positive density that $\gamma_{n+1} - \gamma_n \geq 1/\gamma_n^\epsilon$. Here we assume that for some $\theta > 0$ for all $n \in \mathbb{N}$

$$\gamma_{n+1} - \gamma_n \gg \frac{1}{\gamma_n^\theta},$$

where the implied constant depends on θ , but is absolute once θ has a numerical value. Call this assumption the “zero separation conjecture” or ZSC. Of course, if it is true, it implies all zeros are simple. It supports the notion of Montgomery that the zeros tend to “repel”, but does allow zeros to be very close. In [11] Gonek suggests $\theta = 1/3 + \epsilon$ might be the optimal choice.

Theorem 4.2. *Assume RH and ZSC. Then for all $n \in \mathbb{N}$,*

$$\log T_n \ll \gamma_n^{2+\theta}.$$

Proof. Using the shifted product representation for $\xi(s)$,

$$\xi(z + \frac{1}{2}) = \xi(\frac{1}{2}) \prod_{n \in \mathbb{N}} (1 + \frac{z^2}{\gamma_n^2})$$

leads to the value of the derivative at a zero,

$$\begin{aligned} u_t(\frac{1}{2}, \gamma_n) &= \frac{2\xi(\frac{1}{2})}{\gamma_n} \prod_{j \in \mathbb{N}, j \neq n} (1 - \frac{\gamma_n^2}{\gamma_j^2}) \\ |u_t(\frac{1}{2}, \gamma_n)| &= \frac{2\xi(\frac{1}{2})}{\gamma_n} \prod_{1 \leq j < n} (\frac{\gamma_n^2}{\gamma_j^2} - 1) \prod_{n < j} (1 - \frac{\gamma_n^2}{\gamma_j^2}) \\ &= \frac{2\xi(\frac{1}{2})}{\gamma_n} X_n \times Y_n, \text{ say.} \end{aligned}$$

Because the number of zeros up to level T is less than $T \log T / 2\pi$, it follows that

$$X_n = \prod_{1 \leq j < n} (\frac{\gamma_n + \gamma_j}{\gamma_j})(\frac{\gamma_n - \gamma_j}{\gamma_j}) \geq (\frac{\gamma_n - \gamma_{n-1}}{\gamma_n})^{\gamma_n \log \gamma_n}.$$

Therefore, by the assumption ZSC,

$$(1) \quad -\log X_n \ll (\theta + 1)\gamma_n \log^2 \gamma_n.$$

Also, because $-\log(1 - x) \leq x/(1 - x)$ for $0 \leq x < 1$ and

$$Y_n = \prod_{j > n} (1 - \frac{\gamma_n^2}{\gamma_j^2}), \text{ then}$$

$$(2) \quad -\log Y_n = \sum_{j > n} -\log(1 - \frac{\gamma_n^2}{\gamma_j^2}) \leq \sum_{j > n} \frac{\gamma_n^2}{\gamma_j^2 - \gamma_n^2}.$$

But

$$\begin{aligned} \sum_{j>n} \frac{1}{\gamma_j^2 - \gamma_n^2} &= \sum_{\gamma_j^2 < \frac{10}{9}\gamma_n^2} \frac{1}{\gamma_j^2 - \gamma_n^2} + \sum_{\gamma_j^2 \geq \frac{10}{9}\gamma_n^2} \frac{1}{\gamma_j^2 - \gamma_n^2} \\ &= S_1 + S_2, \text{ say.} \end{aligned}$$

Since, in S_2 , $\gamma_j^2 - \gamma_n^2 \geq \gamma_j^2 - \frac{9}{10}\gamma_j^2 = \frac{1}{10}\gamma_j^2$,

$$S_2 \leq \sum_{\gamma_j^2 \geq \frac{10}{9}\gamma_n^2} \frac{10}{\gamma_j^2} \ll \frac{\log^2 \gamma_n}{\gamma_n}.$$

The sum S_1 is finite with largest term being the first, which is

$$\frac{1}{(\gamma_{n+1} + \gamma_n)(\gamma_{n+1} - \gamma_n)} \ll \frac{\gamma_n^\theta}{2\gamma_n}.$$

The number of terms is bounded by

$$\int_{\gamma_n}^{\sqrt{10/9}\gamma_n} \log t \, dt = O(\gamma_n \log \gamma_n),$$

so

$$S_1 \ll \gamma_n^\theta \log \gamma_n$$

and therefore by (2)

$$(3) \quad -\log Y_n \ll \gamma_n^2 (\gamma_n^\theta \log \gamma_n + \frac{\log^2 \gamma_n}{\gamma_n}) \ll \gamma_n^{2+\theta}.$$

It follows from (1) and (3) that

$$\log T_n \ll -\log |u_t(\frac{1}{2}, \gamma_n)| \ll \gamma_n^{2+\theta}. \quad \square$$

Gonek [11] defines

$$\Theta = \inf\{\theta : |\zeta'(\frac{1}{2} + i\gamma_n)|^{-1} = O(|\gamma_n|^\theta) \text{ for all } n\}.$$

Then [12] the Riemann Hypothesis implies $\Theta \geq 0$ and the averaged Mertens hypothesis ([17, Section 14.29]) implies $\Theta \leq 1$. Gonek, on the basis of an analogy with eigenvalue statistics for random unitary matrices, conjectures $\Theta = 1/3$. Hughes, Keating and O’Connell [12], following Gonek, surmise that $\Theta = 1/3$ is in line with Montgomery’s pair correlation conjecture [14, 16], which suggests $\Theta \geq 1/3$. To summarise this heuristic argument, the pair correlation conjecture [14] statement is that for fixed a, b with $0 < a \leq b < \infty$, as $T \rightarrow \infty$,

$$\frac{|\{(\gamma, \gamma') : 0 < \gamma, \gamma' \leq T, \frac{2\pi a}{\log T} \leq \gamma - \gamma' \leq \frac{2\pi b}{\log T}\}|}{T \log T / (2\pi)} \sim \int_a^b (1 - (\frac{\sin \pi x}{\pi x})^2) dx.$$

Then a is set to 0 and b small so that the integral may be approximated by $\pi^2 b^3$. Even though the conjecture is true for $T \rightarrow \infty$, assuming it holds for “small” T leads to the inequality $b \gg T^{-1/3}$ so $\gamma_{n+1} - \gamma_n \gg \gamma_n^{-1/3}$. Finally assuming the reverse of an argument similar to that used in Theorem 4.3 below holds, we are led to suppose $\Theta \gg 1/3$.

Here we assume the Riemann Hypothesis and just $\Theta < \infty$, namely, that there exists a $\theta \geq 0$ such that

$$|\zeta'(\frac{1}{2} + i\gamma_n)|^{-1} = O(|\gamma_n|^\theta)$$

for all $n \in \mathbb{N}$. We call this assumption WG or weak Gonek.

Theorem 4.3. *Assume the Riemann Hypothesis and WG. Then for all n*

$$\log T_n \leq \frac{\pi}{4}\gamma_n + O(\log \gamma_n).$$

Proof. Using Stirling’s approximation to the Gamma function with $\rho_n = \frac{1}{2} + i\gamma_n$,

$$\begin{aligned} \log T_n &= \log 2\pi - \log |\xi'(\frac{1}{2} + i\gamma_n)| \\ &= \log 2\pi - \log \left| \frac{\rho_n(\rho_n - 1)}{2} \right| - \log |\pi^{-\rho_n/2}| - \log |\Gamma(\rho_n/2)| - \log |\zeta'(\rho_n)| \\ &= -\log |\Gamma(1/4 + i\gamma_n/2)| - \log |\zeta'(\rho_n)| + O(\log \gamma_n) \\ &= \frac{\pi}{4}\gamma_n + \log(1/|\zeta'(\rho_n)|) + O(\log \gamma_n), \end{aligned}$$

and the result follows. □

The final equation in this proof can then be used to show

Corollary 4.1. *Assume the Riemann Hypothesis. Then WG is true if and only if*

$$\log T_n \leq \frac{\pi}{4}\gamma_n + O(\log \gamma_n).$$

Theorem 4.4. *Assume the Riemann Hypothesis. Then if WG is true there exists $\theta_1 > 0$ such that, for all $n \in \mathbb{N}$,*

$$\gamma_{n+1} - \gamma_n \gg \frac{1}{\gamma_n^{\theta_1}}.$$

Proof. Expand $f(t) = \zeta(\frac{1}{2} + it)$, using Taylor’s theorem about γ_n as far as γ_{n+1} . There is an η between γ_n and γ_{n+1} such that

$$f(\gamma_{n+1}) = f(\gamma_n) + if'(\gamma_n)(\gamma_n - \gamma_{n+1}) - \frac{1}{2}f''(\eta)(\gamma_n - \gamma_{n+1})^2,$$

so $\gamma_{n+1} - \gamma_n = 2|f'(\gamma_n)|/|f''(\eta)|$.

By Lemma 3.4

$$|\zeta''(\frac{1}{2} + i\eta)| \ll \eta^{1/4} \log^4 \eta \leq \gamma_{n+1}^{1/4} \log^4 \gamma_{n+1} \ll \gamma_n^{1/4} \log^4 \gamma_n.$$

Hence

$$\gamma_{n+1} - \gamma_n \gg \frac{1}{\gamma_n^\theta \gamma_n^{1/4} \log^4 \gamma_n} \gg \frac{1}{\gamma_n^{\theta+1/4+\epsilon}},$$

so we can choose $\theta_1 = \theta + 1/4 + \epsilon$. □

5. HILBERT–POLYA CONJECTURE

The well-known approach to proving the Riemann Hypothesis, attributed to Polya and Hilbert [15], is that there is a naturally occurring Hermitian operator whose eigenvalues are the zeros of $\xi(\frac{1}{2} + it)$, which are therefore real [7, Page 345]. There have been many attempts to find such an operator [1], but none so far has been completely successful. The normal interpretation of the heights of the zeros $\{\gamma_n : n \in \mathbb{N}\}$ is that they correspond to frequencies of some, to be determined, vibrating system.

Consideration of the phase portraits described in [5, 6] in the light of the constancy of the period for rotation about each simple zero on the critical line [3,

Theorem 2.3], gives rise to the notion that an alternative set of potential eigenvalues might be related to these periods $\{T_n : n \in \mathbb{N}\}$ in the usual manner:

$$f_n = \frac{1}{T_n} = \frac{\lambda_n}{2\pi} = \frac{|u_t(\frac{1}{2}, \gamma_n)|}{2\pi} \approx \frac{e^{-\frac{\pi\gamma_n}{4}}}{2\pi},$$

so $\lambda_i \approx e^{-\frac{\pi\gamma_i}{4}}$. This approach has the following features:

- (a) The eigenvalues have a natural relationship to $\zeta(s)$.
- (b) The eigenvalues are the natural frequencies occurring in the flow $\dot{s} = \xi(s)$.
- (c) The lowest zero corresponds to the largest eigenvalue and therefore to the mode of highest energy and largest frequency. This is quite natural, since the values of $\xi(s)$ with s real and with values which are large and positive might be regarded as exerting a strong attractive pull on the flow, and would be expected to generate the greatest energy in the closest pair of zeros, in which corresponding frequencies become the “fundamental” modes. This “attractor” concept is strongly reinforced by the structure of the separatrices which all tend to the real axis [5, Theorem 3.2]. This is much more satisfactory than the normal approach in which the energy increases as the distance away from the real axis increases.

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