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The growth of entire and harmonic functions along asymptotic paths

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1. Introduction

In a recent paper of Lewis and the two authors [5], the following generalization of a theorem of Huber [4] is proved.

THEOREM A. *Let f be a transcendental entire function. Then there exists a path Γ from 0 to ∞ such that*

$$\lim_{\substack{z\to\infty\\ z\in\Gamma}} \frac{\log|f(z)|}{\log|z|}=\infty \tag{1.1}$$

$$l(\Gamma(z))\le|f(z)|^{\varepsilon(z)} \quad (0\le\varepsilon(z)\to 0,\ z\to\infty) \tag{1.2}$$

where $l(\Gamma(z))$ is the length of Γ from 0 to z and

$$\int_\Gamma \frac{1}{|f|^\lambda}|dz|<\infty \quad (\textit{for all } \lambda>0). \tag{1.3}$$

In [7], one of the authors has proved.

THEOREM B. *Let f be an entire function such that for some $K>0$ at least one of the level curves $|f|=K$ tends to ∞. Then there exists a path Γ from 0 to ∞ such that*

$$\log|f(z)|>|z|^{1/2-\varepsilon(z)} \tag{1.4}$$

and

$$l(\Gamma(z))\le(\log|f(z)|)^{c+2+\varepsilon(z)} \tag{1.5}$$

where $c>0$ is an absolute constant and $0\le\varepsilon(z)\to 0$ as $z\to\infty$.

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[1] Research carried out as a NATO Postdoctoral Fellow at Imperial College, London.

In this paper we prove

THEOREM 1. *Let f be as in Theorem* B. *Then there exists a path Γ from* 0 *to* ∞ *such that* (1.4) *holds and*

$$\int_\Gamma (\log|f|)^{-(2+\lambda)}|dz|<\infty \quad (\textit{for all } \lambda>0). \tag{1.6}$$

Whereas (1.1) and (1.2) imply (1.3), we note that because of the presence of c, (1.4) and (1.5) do not imply (1.6). The constant c is a by-product of the proof of Theorem B. We use a totally different approach in proving Theorem 1.

COROLLARY 1. *Let u be a nonconstant harmonic function in* $\mathbb{C}$. *Then there exists a path Γ from* 0 *to* ∞ *such that* (1.4) *and* (1.6) *hold with* $\log|f|$ *replaced by u.*

The proof of Corollary 1 is immediate from Theorem 1. Indeed, if u is any such harmonic function and v is its harmonic conjugate in $\mathbb{C}$ then $f=e^{u+iv}$ is transcendental and entire with $u=\log|f|$. Clearly by the harmonicity of u every level curve of $|f|=1$ $(u=0)$ extends to ∞.

We also prove

THEOREM 2. *Let f be an entire function of order $\rho\leqq\infty$ such that for some $K>0$ the set $\{z:|f|>K\}$ contains at least two components. Then there exists a path Γ from* 0 *to* ∞ *such that*

$$\log|f(z)|>|z|^{[\rho/(2\rho-1)]-\varepsilon(z)} \quad (0\leq\varepsilon(z)\to 0 \textit{ as } z\to\infty) \tag{1.7}$$

and

$$\int_\Gamma (\log|f|)^{-[(2\rho-1)/\rho]+\lambda}|dz|<\infty \quad (\textit{for all } \lambda>0). \tag{1.8}$$

(We note that by hypothesis and an easy application of the Ahlfors, Denjoy, Carleman method, $\rho\geq 1$ and thus $(2\rho-1)/\rho\geq\frac{1}{2}$.)

Examples in Eremenko [3 p. 681] show that $\varepsilon(z)$ cannot be replaced by 0 in (1.4) and (1.6).

By modifying his examples slightly, we can find an entire function f of order ρ, $1\leq\rho\leq\infty$ such that

$$\int_\Gamma (\log|f(z)|)^{-(2\rho-1)/\rho}|dz|=\infty$$

for every path Γ on which $|f|>1$. This shows that (1.5) and (1.7) are "sharp" independent of (1.4) and (1.6).

Barth, Brannan and Hayman [2, Theorem 2] show that $\varepsilon(z)$ cannot be replaced by 0 in (1.4) where $\log|f|=u$ is harmonic. Brannan has pointed out in private communication that their example can be modified to show that (1.5) is also "sharp" for harmonic functions. Specifically one can construct a harmonic function u such that

$$\int_\Gamma u(z)^{-2}|dz|=\infty$$

for all paths Γ where $u>0$.

2. Preliminary lemmas

Let D be an unbounded regular plane domain. We let $\theta^*(r)=\infty$ if $\{|z|=r\}\subseteq D$. Otherwise we let $r\theta^*(r)$ equal the length of the longest arc in the intersection of $\{|z|=r\}$ and D. Recall that a set G has log density one if $(\log r)^{-1}\int_{G\cap[1,r]}dt/t\to 1$ as $r\to\infty$. We state

LEMMA 1. *Let D be as above and suppose*

$$\inf_G \overline{\lim_{\substack{r\to\infty\\ r\in G}}}\, \theta^*(r)=\frac{\pi}{\alpha}\quad (\tfrac{1}{2}\le\alpha<\infty) \tag{2.1}$$

where the inf *is taken over all sets G of log density one. Then there exists $v>0$ harmonic in D such that for all $z\in D$*

$$v(z)\ge|z|^{\alpha-\varepsilon(|z|)}\quad (0\le\varepsilon(|z|)\to 0\quad\text{as}\quad |z|\to\infty). \tag{2.2}$$

We remark that without the log density statement, (2.2) was proved in [2] with $\alpha=\frac{1}{2}$.

Before we prove Lemma 1 we need the following lemma which asserts that the inf in (2.1) is attained.

LEMMA 2. *There exists a set G of log density one such that*

$$\overline{\lim_{\substack{r\to\infty\\ r\in G}}}\, \theta^*(r)=\frac{\pi}{\alpha}. \tag{2.3}$$

Proof. Let l.m. $(E)=\int_E dt/t$ for any measurable set $E\subseteq[0,\infty)$. By (2.1) we may find G_n, $n=1,2,\ldots$ such that

$$\theta^*(r)\leq\frac{\pi}{\alpha}+\frac{1}{n} \tag{2.4}$$

and

$$\text{l.m. }(G_n\cap[1,r])\geq\left(1-\frac{1}{n}\right)\log r \tag{2.5}$$

provided $r\in G_n$, $r\geq r_n$. We may choose r_n so large that

$$\frac{1}{n-1}\log r_n\geq\log r_{n-1},\qquad n=2,3,\ldots \tag{2.6}$$

Define $G=\bigcup_{n=1}^{\infty}G_n\cap[r_n,r_{n+1}]$. To see that log dens $G=1$, choose $\varepsilon>0$ and let N be such that $3/N<\varepsilon$. Suppose $r\in G$ and $r_n\leq r<r_{n+1}$ for some $n\geq N+1$. We have by (2.5) and (2.6)

$$\begin{aligned}
\text{l.m. }(G\cap[1,r])&\geq\text{l.m. }(G_{n-1}\cap[r_{n-1},r_n])+\text{l.m. }(G_n\cap[r_n,r])\\
&\geq\left(1-\frac{1}{n-1}\right)\log r_n-\log r_{n-1}+\left(1-\frac{1}{n}\right)\log r-\log r_n\\
&=-\frac{1}{n-1}\log r_n-\log r_{n-1}+\left(1-\frac{1}{n}\right)\log r\\
&\geq-\frac{2}{n-1}\log r_n+\left(1-\frac{1}{n}\right)\log r\\
&\geq\left(1-\frac{3}{n-1}\right)\log r\\
&\geq\left(1-\frac{3}{N}\right)\log r\\
&\geq(1-\varepsilon)\log r.
\end{aligned}$$

Since ε was arbitrary G has log density one.

Furthermore given $\varepsilon>0$, there exists N such that $1/N<\varepsilon$ and if $r\geq r_N$ we have by (2.4) and the definition of G that $\theta^*(r) \le (\pi/\alpha) - \varepsilon$. This implies

$$\varlimsup_{\substack{r\to\infty\\ r\in G}} \theta^*(r) \le \frac{\pi}{\alpha}. \tag{2.7}$$

Since G has log density one, (2.7) and (2.1) imply (2.4). Lemma 2 is now proved.

Proof of Lemma 1. We denote by $\eta_i(r)$, $i = 1, 2, \ldots$ any nonnegative sequences such that $\eta_i(r) \to 0$ as $r \to \infty$. Then with G as in Lemma 2, we have

$$\theta^*(r) \le \frac{\pi}{\alpha - \eta_1(r)} \quad (r \in G). \tag{2.8}$$

Also if $a \in E$ where E is compact in $\mathbb{C}$ and $|a| \ge 1$

$$\text{l.m.}\,(G \cap [|a|, r] \ge [1 - \eta_2(r)] \log \frac{r}{|a|} \tag{2.9}$$

uniformly in E.

By (2.8) we have

$$\int_{G\cap[|a|,\, r]} \frac{\eta_1(t)}{t}\, dt \le \eta_3(r) \log \frac{r}{|a|}. \tag{2.10}$$

uniformly in E.

Let D_R be any component of $D \cap \{|\zeta| < R\}$. Pick $z \in D_R$ with $|z| < R/4$ and let $\omega_R(z)$ be the harmonic measure of $\{|\zeta| = R\} \cap \partial D_R$ with respect to z and D_R. Then by an inequality found in [8, p. 116] we have

$$\omega_R(z) \le 9\sqrt{2} \exp\left\{-\pi \int_{2|z|}^{R/2} \frac{dt}{t\theta^*(t)}\right\}. \tag{2.11}$$

By (2.8)–(2.11) we have for $z \in E$ compact in $\mathbb{C}$

$$\omega_R(z) \le K\left(\frac{|z|}{R}\right)^{\alpha - \eta_4(R)} \tag{2.12}$$

where K is a constant depending only on E.

Let $\phi(r)$ be any convex increasing function of $\log r$ such that

$$\frac{\log \phi(r)}{\log r} \to \alpha \quad (r \to \infty) \tag{2.13}$$

and

$$\phi(2r) \leq \frac{r^{\alpha-\eta_4(r)}}{(\log r)^2}. \tag{2.14}$$

We now employ a technique similar to the one used in Lemma 1 of [2]. Let D_R be as above. Then there exists a unique function $v_R(z)$ harmonic in D_R, continuous in $\bar{D}_R$ such that for $z \in \partial D_R$

$$v_R(z) = \phi(|z|). \tag{2.15}$$

Let $R_n = 2^n$, $n = 0, 1, 2, \ldots$ and define D_{R_n} as before making sure that $D_{R_{n+1}} \supseteq D_{R_n}$. Let $\omega_{n,\nu}$, $n \geq \nu$ be the harmonic measure in D_{R_n} of the portion of ∂D_{R_n} in $\{|\zeta| \geq R_\nu\}$. Then for all $z \in D_{R_n}$, $|z| \leq R_\nu/4$, we have

$$\omega_{n,\nu}(z) \leq \omega_{R_\nu}(z). \tag{2.16}$$

Choose R_k to be the smallest radius greater than $4|z|$. Then for $z \in D_{R_n} \cap \{|z| \leq R_k/4\}$, $n \geq k$, we have by (2.12), (2.16) the definition of ϕ, and the fact that $|z| \geq R_k/8$,

$$\begin{aligned} v_{R_n}(z) &\leq \phi(R_k) + \sum_{\nu=k}^{n-1} \phi(R_{\nu+1})\omega_{n,\nu}(z) \\ &\leq \phi(8|z|) + k|z|^\alpha \sum_{\nu=k}^{n-1} \phi(R_{\nu+1}) R_\nu^{-\alpha+\eta_4(R_\nu)} \\ &\leq \phi(8|z|) + k|z|^\alpha\left(1 + \sum_{\nu=k}^{\infty} \frac{1}{(\nu+1)^2}\right) \\ &\leq k_1 |z|^\alpha \end{aligned} \tag{2.17}$$

where $k_1 > 0$ is a constant depending only on the compact set $|z| \leq R_K/4$.

Since ϕ is a convex function of $\log r$, we have that $\phi(|z|) - v_{R_n}(z)$ is subharmonic in D_{R_n} and equal to 0 on ∂D_{R_n}. Thus for $z \in D_{R_n}$ we have

$$v_{R_n}(z) \geq \phi(|z|). \tag{2.18}$$

Also if $m \geq n$ and $z \in D_{R_n}$ we have

$$v_{R_m}(z) \geq v_{R_n}(z). \tag{2.19}$$

By (2.17)–(2.19), v_{R_n} is an increasing sequence of harmonic functions uniformly bounded on compact sets. By Harnack's Theorem $v(z) = \lim_{n\to\infty} v_{R_n}(z)$ is harmonic in D. Thus (2.2) follows easily from (2.13) and (2.18).

3. Proof of Theorem 1 when f has no zeros

We assume first that f has no zeros. Then every level curve of $\log|f| = 1$ extends to ∞. Thus if D is any component of $\{z : \log|f| > 1\}$, D is simply connected and contains no full circle $|z| = r$ for $r \geq r_0$. Thus we may find a function v harmonic in D satisfying (2.2) for $\alpha = \frac{1}{2}$. Now let $z_0 \in D$. We can find $\delta > 0$ such that

$$\log|f(z_0)| - \delta v(z_0) > 1. \tag{3.1}$$

Define $w = \delta v$ and let w^* be the harmonic conjugate of w in D. Then $\phi = e^{w+iw^*}$ is analytic in D with no zeros such that

$$\log|\phi| = w \tag{3.2}$$

satisfies (2.2) (for possibly another $\varepsilon(z)$).

Set $F = f/\phi$ in D. By (2.2), (3.1) and (3.2) $\log F$ has boundary values on ∂D not exceeding 1 and is greater than 1 at $z_0 \in D$. Thus every component $\mathcal{F}_R$, $R \geq 1$ of $\{z : |F| > R\}$ is nonempty and contained in D.

To construct our path Γ we will use extremal length arguments in each $\mathcal{F}_R$. We define extremal length as in [1. p. 11]. Let $\mathcal{G}$ be a family of curves. The extremal length $\lambda(\mathcal{G})$ of $\mathcal{G}$ is defined as

$$\lambda(\mathcal{G}) = \sup_\rho \frac{L^2(\rho)}{A(\rho)}$$

where

$$L(\rho) = \inf_{\gamma\in\mathcal{G}} \int_\gamma \rho\,|dz|, \qquad A(\rho) = \iint_{\mathbb{C}} \rho^2\,dx\,dy$$

and $\rho \geq 0$ ranges over all measurable functions for which $A(\rho) \neq 0, \infty$.

To get the construction started let $R_0 > e$ be such that $F' \neq 0$ when $|F| = R_0$ and take a component $\mathcal{F}_{R_0} \subseteq D$ with $\zeta_0 \in \partial\mathcal{F}_{R_0}$ arbitrarily chosen. It follows from the Cauchy–Riemann equations that $\arg F$ is then monotone on $\partial\mathcal{F}_{R_0}$ so that for some $\eta > 0$ a branch of the function $w = \log F$ maps a neighborhood of an arc of $\partial\mathcal{F}_{R_0}$ containing ζ_0 univalently to a neighborhood of a segment

$$T_0 = \{w = \log R_0 + \mathrm{iv} : \psi_0 - \eta \le v \le \psi_0 + \eta\}$$

with the arc of $\partial\mathcal{F}_{R_0}$ and the segment T_0 corresponding. By replacing F by F^K where K is a sufficiently large positive integer we may assume that η is arbitrarily large. This modification of F will in no way affect our method and so we asume that $\eta = e$ in the definition of T_0.

Recall the function $\varepsilon(r)$ in (2.2). Fix $\lambda_0 > 0$ such that

$$(2+4e)\sum_{j=0}^{\infty}\left(2\pi\int_0^{\infty}\frac{r\,dr}{[e^j - 1 + \log R_0 + r^{\frac{1}{2}-\varepsilon(r)}]^{4+2\lambda_0}}\right)^{1/2} \le 1. \tag{3.4}$$

This is possible since the left side of (3.4) converges for every $\lambda_0 > 0$.

With ψ_0 as chosen, we let Q_0 be the square in the w-plane defined by $Q_0 = \{(s, t_0) : \log R_0 < s < 2e + \log R_0,\ \ \psi_0 - e < t < \psi_0 + e\}$. Set $\gamma = \gamma_{t_0} = \{(s, t_0) : \log R_0 \le s < s'\}$ where t_0 ranges between $\psi_0 - e$ and $\psi_0 + e$ and $s' \le \log R_0 + 2e$. The point s' is chosen to be $\log R_0 + 2e$ if the inverse $h(w)$ of $\log F$ can be uniquely continued on γ_{t_0} from $\log R_0$ to $\log R_0 + 2e$. Otherwise s' is chosen so that (s', t_0) is the first point on the horizontal segment γ_{t_0} where h cannot be continued uniquely. Since $s' > \log R_0$ and since h cannot tend to $\partial\mathcal{F}_{R_0} \subseteq D$ this can only happen if either there exists a point $z_1 \in \mathcal{F}_{R_0}$ such that $\log F(z_1) = (s', t_0)$ and $F'(z_1) = 0$ or if $h \to \infty$ as $w \to (s', t_0)$.

By taking unions over all such horizontal segments and their preimages in the z-plane, we obtain a measurable set $\mathcal{F} \subseteq \mathcal{F}_{R_0}$ which maps 1–1 under $\log F$ to a subset $\tilde{Q}_0$ of Q_0. Let $\mathcal{G}$ be the family of *all* horizontal segments in Q_0 connecting both sides of Q_0. Since Q_0 is a square this implies [1, p. 12] that $\lambda(\mathcal{G}) = 1$. Furthermore since the curves in $\tilde{\mathcal{G}}$ are no "longer" than those in $\mathcal{G}$, we have in the notation of [1, p. 12] that $\tilde{\mathcal{G}} < \mathcal{G}$ and so $\lambda(\tilde{\mathcal{G}}) \le 1$. Let $\tilde{C}$ be the collection of the images under h of those curves in $\tilde{\mathcal{G}}$ which extend all the way across Q_0. Then $\tilde{C} = h(\tilde{\mathcal{G}}) - C_1 - C_2$ where C_1 are the curves which run into points where $F' = 0$ and C_2 are the unbounded curves. But the number of curves in C_1 is countable and the curves in C_2 extend to ∞. Thus it is easy to see [6, Theorems 2.13 and 2.14] that $\lambda(\tilde{C}) = \lambda(h(\tilde{\mathcal{G}}))$. Since $(\log F)' \neq 0$ on $h(\tilde{\mathcal{G}})$, it is easy to show that $\lambda(h(\tilde{\mathcal{G}})) = \lambda(\tilde{\mathcal{G}})$. This gives

$$\lambda(\tilde{C}) \le 1. \tag{3.5}$$

On $\tilde{C}$ we take (in (3.3)) $\rho=\rho_0=(\log|f|)^{-2-\lambda_0}$ and $\rho=0$ off $\tilde{C}$. Clearly $A(\rho)\neq 0$. To show that $A(\rho)\neq\infty$ we have by (2.2), (3.2) and the fact that the union of the $\tilde{C}$ lies in $\mathcal{F}\subseteq\mathcal{F}_{R_0}$

$$\begin{aligned}A(\rho_0)&\leq\iint_{\mathcal{F}}(\log|f|)^{-4-2\lambda_0}r\,dr\,d\theta\\&\leq\iint_{\mathcal{F}}(\log R_0+\delta v)^{-4-2\lambda_0}r\,dr\,d\theta\\&\leqq 2\pi\int_0^{\infty}(\log R_0+r^{\frac{1}{2}-\varepsilon(r)})^{-4-2\lambda_0}r\,dr\\&<\infty.\end{aligned}\tag{3.6}$$

Let us define for R and λ positive

$$K(R,\lambda)=\left(2\pi\int_0^{\infty}(R+r^{\frac{1}{2}-\varepsilon(r)})^{-4-2\lambda}r\,dr\right)^{1/2}.\tag{3.7}$$

Thus it follows by (3.3), (3.6) and (3.7) that there exists in $\tilde{C}$ a curve $\tilde{\beta}_0\subseteq\mathcal{F}_{R_0}$ that joins a point $z\in\partial\mathcal{F}_{R_0}$ to $\partial\mathcal{F}_{e^{2e}R_0}$ for some component $\mathcal{F}_{e^{2e}R_0}\subseteq\mathcal{F}_{R_0}$ of the set $\{z:|F|>e^{2e}R_0\}$. Furthermore

$$\int_{\tilde{\beta}_0}(\log|f|)^{-2-\lambda_0}|dz|\leq 2K(\log R_0,\lambda_0).\tag{3.8}$$

We let $\tilde{\beta}_0$ correspond to γ_{t_0} in Q_0. Then a similar procedure is applied to the rectangle $S_0=\{(s,t):e+\log R_0<s<2e+\log R_0,\quad t_0<t<t_0+2e^2\}$ in the w plane where the bottom of S_0 corresponds to half of $\tilde{\beta}_0$ under a branch h of $(\log F)^{-1}$. Here we consider the family of vertical segments $\gamma=\gamma_{s_0}=\{(s_0,t):t_0-e^2<t<t_0+e^2\}$ in S_0. As before we obtain a family $\tilde{\mathcal{G}}$ whose union is mapped 1–1 onto a set $\xi\subseteq\mathcal{F}_{e^eR_0}$. Since S_0 is a rectangle of length $2e^2$ and width e we obtain with $\tilde{C}$ as before

$$\lambda(\tilde{C})=\lambda(\tilde{\mathcal{G}})\leq\lambda(\mathcal{G})=\frac{2e^2}{e}=2e.$$

So in $\mathcal{E}$ we again get a curve $\tilde{\alpha}_0$ whose image γ_{s_0} under $\log F$ is a vertical segment joining the two sides of S_0 and

$$\int_{\tilde{\alpha}_0}(\log|f|)^{-2-\lambda_0}|dz|\leq 4eK(\log R_0,\lambda_0).\tag{3.9}$$

We now cut $\tilde{\beta}_0$ off where it joins $\tilde{\alpha}_0$ at $\log R_1(\geq \log R_0+e)$ and obtain the first piece $\beta_0 \subseteq \tilde{\beta}_0$ of our curve Γ. With λ_0 still fixed we continue with the square

$$Q_1=\{(s,t):\log R_1<s<2e^2+\log R_1,\ t_0<t<t_0+2e^2\}$$

and obtain a curve $\tilde{\beta}_1$ on which $F'\neq 0$ joining $\tilde{\alpha}_0$ to the boundary of a component $\mathscr{F}_{e^{2e^2}R_1}\subseteq \mathscr{F}_{R_1}$ of the set $\{z:|F|>e^{2e^2}R_1\}$. Then (3.6) becomes

$$\int_{\tilde{\beta}_1}(\log|f|)^{-2-\lambda_0}|dz|\leq 2K(\log R_1,\lambda_0).$$

We now cut $\tilde{\alpha}_0$ off where it joins $\tilde{\beta}_1$ and obtain the second piece α_0 of Γ. Let $\tilde{\beta}_1$ correspond to γ_{t_1} in Q_1 and define the rectangle

$$S_1=\{(s,t):e^2+\log R_1<s<2e^2+\log R_1,\ t_1<t<t_1+2e^3\}.$$

Again we find that the extremal length of the vertical lines joining the two sides of S_1 is $2e$. So we again obtain a curve $\tilde{\alpha}_1$ such that

$$\int_{\tilde{\alpha}_1}(\log|f|)^{-2-\lambda_0}|dz|\leq 4eK(\log R_1,\lambda_0).$$

This process is continued yielding a curve $\beta_0\cup\alpha_0\cup\beta_1\cup\alpha_1\cup\cdots\cup\beta_n\cup\tilde{\alpha}_n$ extending from $\partial\mathscr{F}_{R_0}$ to the boundary of a component $\mathscr{F}_{R_n}$ where

$$\log R_n\geq e^n-1+\log R_0 \qquad n=0,1,2,\ldots \tag{3.10}$$

Our construction yields

$$\int_{\tilde{\beta}_i}(\log|f|)^{-2-\lambda_0}|dz|\leq 2K(\log R_j,\lambda_0)$$

and

$$\int_{\tilde{\alpha}_i}(\log|f|)^{-2-\lambda_0}|dz|\leq 4eK(\log R_j,\lambda_0).$$

Adding these contributions and taking into account (3.4), (3.7) and (3.10) we obtain

$$\int_{\beta_0\cup\alpha_0\cup\cdots\cup\beta_n\cup\tilde{\alpha}_n} (\log|f|)^{-2-\lambda_0}|dz| \le (2+4e)\sum_{j=0}^{\infty} K(\log R_j, \lambda_0)$$

$$\le (2+4e)\sum_{j=0}^{\infty} K(e^j-1+\log R_0, \lambda_0)$$

$$\le 1$$

independent of n. We keep λ_0 fixed until N is so large that

$$(2+4e)\sum_{j=0}^{\infty}\left(2\pi\int_0^{\infty}\frac{r\,dr}{(e^j-1+\log R_N+r^{1/2-\varepsilon(r)})^{4+\lambda_0}}\right)^{1/2}\le\tfrac{1}{2}. \tag{3.11}$$

At this point we change λ_0 to $\lambda_0/2$ with (3.11) playing the role of (3.4). We then continue from the arc $\tilde{\alpha}_n$ where $|F|=R_N$ in place of the original arc γ_0 on $|F|=R_0$. In the general case we obtain a sequence

$$0=N_0<N_1<\cdots<N_j$$

such that

$$\log R_{N_j}\ge e^{N_j-N_{j-1}}+\log R_{N_{j-1}} \qquad j=1,2,\ldots \tag{3.12}$$

The N_j are chosen such that

$$(4+2e)\sum_{n=0}^{\infty} K(e^n-1+\log R_{N_j}, \lambda_0/(j+1))\le 2^{-j} \tag{3.13}$$

with $\beta_{N_j}\cup\alpha_{N_j}\cup\cdots\cup\beta_{N_{j+1}}\cup\tilde{\alpha}_{N_{j+1}}$ extending from $\partial\mathcal{F}_{R_{N_j}}$ to $\partial\mathcal{F}_{R_{N_{j+1}}}$ and satisfying

$$\int_{\beta_{N_j}\cup\alpha_{N_j}\cup\cdots\cup\beta_{N_{j+1}}\cup\alpha_{N_{j+1}}} (\log|f|)^{-2-\lambda_0/(j+1)}|dz|$$

$$\le (4+2e)\sum_{n=0}^{\infty} K(e^n-1+\log R_{N_j}, \lambda_0/(j+1))$$

Let $\Gamma=\beta_0\cup\alpha_0\cup\cdots\cup\beta_k\cup\alpha_k\cup\cdots$ Then since $\log|f|>1$ in D and hence on Γ we have

$$\int_\Gamma (\log|f|)^{-2-\lambda}|dz|<\int_\Gamma(\log|f|)^{-2-\lambda'}|dz|$$

if $\lambda>\lambda'$. Thus it follows from (3.13) and (3.14) that Γ satisfies (1.6) for all $\lambda>0$.

4. Proof of Theorem 1—general case

When f has zeros the proof in §3 must be modified slightly. First of all by hypothesis there exists a component D of $\{z:\log|f(z)|>\log K\}$ such that $\theta^*(r)\leq 2\pi$ for $r\geq r_0$, where we can assume $K>e$. Thus we can still find v satisfying (2.2) and (3.1). Since D is not necessarily simply connected, we can only define a local conjugate of $w=\delta v$ and so our function F is now multivalued. However $|F|$ and $\log|F|$ are single valued and subharmonic in $\mathbb{C}$. Thus we see that $\mathcal{F}_R$ is again nonempty for all $R\geqq K$.

We then proceed as before taking γ_0 to be a level curve of $|F|=R_0$ extending to infinity, where $F'\neq 0$ and find a curve $\tilde{\beta}_0$. We remark that $\tilde{\beta}_0$ never intersects a level curve $|F|=R$, $R_0\leq R\leq R+2e$ which forms a loop. In fact inside such a loop $|F|<R$ so if β_0^* is the portion of $\tilde{\beta}_0$ joining R_0 to R, β_0^* must pass through some point z_0 where $|F(z)|>R$. This is impossible since β_0^* is the image under h of the horizontal segment beginning at $\log R_0$ and ending at $\log R$. Hence we can find an $\tilde{\alpha}_0$ as before. We now continue as in §3.

5. Proof of Theorem 2

To prove Theorem 2 we need the following.

LEMMA 3. *Let f be entire of order $\frac{1}{2}<\rho<\infty$. If D is any component of $\{z:|f(z)|>K\}$, $K>e$ then*

$$\sup_G \varliminf_{\substack{r\to\infty\\ r\in G}} \theta^*(r)\geq\frac{\pi}{\rho} \tag{5.1}$$

where the sup *is taken over all sets G of log density one.*

Proof. Suppose on the contrary that the left side of (5.1) equals π/ρ_1, $\rho_1>\rho$. As in Lemma 2 we may find a set G of log density one where the sup on the left side of (5.1) is attained. Thus for $r\geq r_0$, $r\in G$

$$\theta^*(r)\leq\frac{\pi}{\rho_2}\quad(\rho_1\geq\rho_2>\rho). \tag{5.2}$$

Let $z\in D$ and choose R such that $|z|<R/4$. With the notation of (2.11) we

have

$$\begin{aligned}\omega_R(z) &\leq 9\sqrt{2}\exp\left\{-\rho_2\int_{G\cap[2|z|,\,R/2]}\frac{dt}{t}\right\}\\ &\leq 9\sqrt{2}\exp\left\{-\rho_2(1-\varepsilon_m)\log\left(\frac{R}{|z|}\right)\right\}\\ &= 9\sqrt{2}\left(\frac{|z|}{R}\right)^{\rho_2(1-\varepsilon_m)}\end{aligned} \tag{5.3}$$

where (since log dens $G=1$) $\varepsilon_m \to 0$ as $m\to\infty$. Thus by (2.12) we have for fixed $z\in D_R$

$$\begin{aligned}1 \leq \log|f(z)| &\leq \log K + \log M(R,f)\omega_R(z)\\ &\leq K_1 \log M(R,f)\left(\frac{|z|}{R}\right)^{\rho_2(1-\varepsilon_m)}\end{aligned}$$

where $K_1>0$ is constant. Then

$$\log M(R,f) \geq \frac{1}{K_1}\left(\frac{R}{|z|}\right)^{\rho_2(1-\varepsilon_m)}.$$

Since z is fixed this implies that f has order at least $\rho_2>\rho$, a contradiction. Thus (5.1) holds and Lemma 3 is true.

Proof of Theorem 2. Let D_1 be a component of $\{|f|>K\}$ and suppose

$$\inf_G \varlimsup_{\substack{r\to\infty\\ r\in G}} \theta_1^*(r) = \frac{\pi}{\alpha} \quad (\tfrac{1}{2}\leq\alpha<\infty) \tag{5.4}$$

where the inf is taken over all sets G, log dens $G=1$ and θ_1^* corresponds to θ^* for D_1. Since there exists another component D_2 of $\{|f|>K\}$, (5.4) implies

$$\sup_G \varliminf_{\substack{r\to\infty\\ r\in G}} \theta_2^*(r) \leq 2\pi - \frac{\pi}{\alpha} \tag{5.5}$$

where θ_2^* corresponds to θ^* for D_2.

By Lemma 3 we must have

$$\frac{\pi}{\rho} \le 2\pi - \frac{\pi}{\alpha}$$

or

$$\alpha \ge \frac{\rho}{2\rho - 1}. \tag{5.6}$$

By Lemma 1, (5.4) and (5.6) we may find a function v harmonic in D_1 such that for all $z \in D_1$

$$v(z) \ge |z|^{[\rho/(2\rho-1)]-\varepsilon(|z|)} \quad (0 \le \varepsilon(|z|) \to 0 \quad \text{as} \quad |z| \to \infty). \tag{5.7}$$

We now define ϕ and F as in the proof of Theorem 1. The proof of Theorem 2 now follows in the same way as that of Theorem 1 using $\rho/(2\rho-1)$ instead of $\frac{1}{2}$.

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