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INEQUALITIES FOR ZERO-BALANCED HYPERGEOMETRIC FUNCTIONS

G. D. ANDERSON, R. W. BARNARD, K. C. RICHARDS,
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ABSTRACT. The authors study certain monotoneity and convexity properties of the Gaussian hypergeometric function and those of the Euler gamma function.

1. INTRODUCTION

The Gaussian *hypergeometric function* is defined by

$$(1.1) \quad F(a, b; c; x) = {}_2F_1(a, b; c; x) = \sum_{n=0}^{\infty} \frac{(a, n)(b, n)}{(c, n)} \frac{x^n}{n!},$$

for $x \in (-1, 1)$, where (a, n) denotes the shifted factorial function $(a, n) = a(a+1)\cdots(a+n-1)$, $n = 1, 2, \dots$, and $(a, 0) = 1$ for $a \neq 0$. The sum is well defined at least when $(c, n) \neq 0$, i.e., when $c \neq 0, -1, -2, \dots$. This function has found frequent applications in various fields of the mathematical and natural sciences [Ask2]. Many elementary transcendental functions are special cases or limiting cases of $F(a, b; c; x)$; for an extensive list see [AS, pp. 556–566], [PBM, pp. 430–615]. Two important special cases are the complete elliptic integrals

$$(1.2) \quad \mathcal{K}(x) = \frac{\pi}{2} F\left(\frac{1}{2}, \frac{1}{2}; 1; x^2\right), \quad \mathcal{E}(x) = \frac{\pi}{2} F\left(-\frac{1}{2}, \frac{1}{2}; 1; x^2\right).$$

As a function of its parameters a, b, c the function $F(a, b; c; x)$ is smooth, and it is thus natural to expect that the properties of $\mathcal{K}(x)$ extend also to $F(a, b; c; x^2)$ for (a, b, c) close to $(\frac{1}{2}, \frac{1}{2}, 1)$. Recall that $F(a, b; c; x)$ is called *zero-balanced* if $c = a + b$. We obtain several results for the zero-balanced $F(a, b; a + b; x)$, $a, b > 0$, extending well-known properties of $\mathcal{K}(x)$.

1.3. Theorem. (1) For $a, b \in (0, \infty)$ the function

$$f(x) \equiv \frac{1 - F(a, b; a + b; x)}{\log(1 - x)}$$

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is strictly increasing from $(0, 1)$ onto $(ab/(a + b), 1/B)$, where $B = B(a, b)$ is the Euler beta function.

(2) For $a, b \in (0, \infty)$ the function

$$g(x) \equiv BF(a, b; a + b; x) + \log(1 - x)$$

is strictly decreasing from $(0, 1)$ onto (R, B) , where

$$R = -\Psi(a) - \Psi(b) - 2\gamma.$$

Here $\Psi(a) = \Gamma'(a)/\Gamma(a)$, and γ is the Euler-Mascheroni constant.

1.4. **Theorem.** For $a, b \in (0, \infty)$, let

$$f(x) = xF(a, b; a + b; x)/\log(1/(1 - x))$$

on $(0, 1)$ and let B, R be as in Theorem 1.3.

(1) If $a, b \in (0, 1)$, then f is decreasing with range $(1/B, 1)$.

(2) If $a, b \in (1, \infty)$, then f is increasing with range $(1, 1/B)$.

(3) If $a = b = 1$, then $f(x) = 1$ for all $x \in (0, 1)$.

(4) If $a, b \in (0, 1)$ the function $g_1(x) \equiv BF(a, b; a + b; x) + (1/x)\log(1 - x)$ is increasing from $(0, 1)$ onto $(B - 1, R)$.

(5) If $a, b \in (1, \infty)$, then g_1 is decreasing from $(0, 1)$ onto $(R, B - 1)$.

Here Theorem 1.3(1) generalizes the fact that $((2/\pi)\mathcal{K}(x) - 1)/\log(1/x')$ is increasing from $(0, 1)$ onto $(1/2, 2/\pi)$; 1.3(2) generalizes the well-known fact that $\mathcal{K}(x) + \log x'$ is decreasing from $(0, 1)$ onto $(\log 4, \pi/2)$ (cf. [AVV1, Theorem 2.2(2)]); and 1.4(1) generalizes the result that $x^2\mathcal{K}(x)/\log(1/x')$ is decreasing from $(0, 1)$ onto $(1, \pi)$ [AVV3, Theorem 2(19)].

The asymptotic relation

$$(1.5) \quad F(a, b; a + b; x) \sim -\frac{1}{B(a, b)} \log(1 - x)$$

as $x \rightarrow 1$ is due to Gauss, and its refined form

$$(1.6) \quad B(a, b)F(a, b; a + b; x) + \log(1 - x) = R + O((1 - x)\log(1 - x))$$

as $x \rightarrow 1$, with $R = -\Psi(a) - \Psi(b) - 2\gamma$, is due to S. Ramanujan [Ev, p. 553], [Be, p. 71]. Theorems 1.3 and 1.4 are refinements of these classical relations. Ramanujan also gave extensions of (1.6) to the generalized hypergeometric function ${}_pF_q$ for certain values of p and q [Ev, pp. 553–558], [Be, pp. 12, 71]. Formulas (1.5) and (1.6) follow from the identity in [AS, 15.3.10], which has been generalized recently in [B, p. 152].

1.7. **Theorem.** For each $a, b \in (0, \infty)$ the function

$$f(x) \equiv (1 - x)^{1/4}F(a, b; a + b; x)$$

is a strictly decreasing automorphism of $(0, 1)$ if and only if $4ab \leq a + b$.

While studying relationships between the arithmetic-geometric mean and some other means, J. and P. Borwein [BB2, (2.9)] recently proved that

$$(1.8) \quad F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^c\right) < F\left(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^d\right)$$

for all $x \in (0, 1)$, with $c = 2, d = 3, \delta = \frac{1}{6}$.

We obtain the following generalization.

1.9. **Theorem.** For $c, d \in (0, \infty)$, $4c < \pi d$, inequality (1.8) holds for all $x \in (0, 1)$ and for all $\delta \in (0, \delta_0)$, where $\delta_0 = ((d\pi - 4c)/(4\pi d))^{1/2}$.

We conclude the paper by proving some inequalities for the gamma function. Our notation is mostly standard. For $x \in [0, 1]$, we often denote $x' = \sqrt{1 - x^2}$.

2. PROOFS

For many important properties of the functions $F(a, b; c; x)$, $\mathcal{K}(x)$, and $\mathcal{E}(x)$ see [AS, pp. 556–566, 589–626], [C, Chapters 2, 9], [PBM, pp. 430–615]. Some algorithms for computing these functions are given in [Ba, pp. 345–372, 416–424], [M, Chapter 7], [PNB, p. 249], and [PT, pp. 404–426]. Various aspects of the theory of special functions are surveyed in [Ask1], [Ask2], [AVV3], [LO, 5.3, 5.5].

We shall give here a proof of the Gauss asymptotic formula (1.5), since we have been unable to find a proof in the recent literature or in the standard texts. Various generalizations of (1.5) appear in [Ev, pp. 553–558], [B, p. 152].

2.1. **Lemma.** (1) For $a, b \in (0, \infty)$, the sequence

$$f(n) \equiv \frac{(a, n)(b, n)}{(a + b, n)(n - 1)!}$$

is increasing to the limit $1/B(a, b)$, as $n \rightarrow \infty$.

(2) For $a, b \in (0, 1)$, the sequence

$$g(n) \equiv \frac{(a, n)(b, n)(n + 1)}{(a + b, n)n!}$$

is decreasing to the limit $1/B(a, b)$, as $n \rightarrow \infty$.

(3) For $a, b \in (1, \infty)$, the sequence $g(n)$ is increasing to the limit $1/B(a, b)$, as $n \rightarrow \infty$.

In particular, for each positive integer n ,

$$(4) \quad \frac{ab}{a + b} \leq f(n) < \frac{1}{B(a, b)} \quad \text{for all } a, b \in (0, \infty),$$

$$(5) \quad \frac{1}{B(a, b)} < g(n) \leq \frac{2ab}{a + b} \quad \text{for all } a, b \in (0, 1),$$

$$(6) \quad \frac{2ab}{a + b} \leq g(n) < \frac{1}{B(a, b)} \quad \text{for all } a, b \in (1, \infty),$$

where the weak inequalities reduce to equality if and only if $n = 1$.

Proof. Part (1) is proved in [AVV3, Theorem 6(4)]. For (2) and (3),

$$\frac{g(n + 1)}{g(n)} = \frac{(a + n)(b + n)(n + 2)}{(a + b + n)(n + 1)^2} < 1$$

iff $w_1 \equiv ((a + b + n)n + ab)(n + 2) < w_2 \equiv (a + b + n)(n + 1)^2$, which is true since $w_2 - w_1 = (a + b - 2ab) + n(1 - ab)$ is positive if $a, b \in (0, 1)$, and negative if $a, b \in (1, \infty)$. The limiting values follow from Stirling's formula [C, p. 24], [Mi, p. 184]. \square

2.2. *Remark.* The following inequalities due to Wallis appear in [Mi, p. 192]:

$$\frac{1}{\sqrt{\pi(n + \frac{1}{2})}} < \frac{(\frac{1}{2}, n)}{n!} < \frac{1}{\sqrt{\pi n}}.$$

Since $B(\frac{1}{2}, \frac{1}{2}) = \pi$, the result in Lemma 2.1(4) generalizes the second Wallis inequality here.

2.3. **Lemma (Gauss).** For $a, b \in (0, \infty)$, the relation (1.5) holds.

Proof. Let $B = B(a, b)$. From Lemma 2.1, we have

$$F(a, b; a + b; x) = \sum_{n=0}^{\infty} \frac{(a, n)(b, n)}{(a + b, n)n!} x^n \leq 1 + \sum_{n=1}^{\infty} \frac{1}{B} \frac{x^n}{n} = 1 - \frac{1}{B} \log(1 - x).$$

Hence

$$\limsup_{x \rightarrow 1} \frac{F(a, b; a + b; x)}{\log(1/(1 - x))} \leq \frac{1}{B}.$$

Next, fix $\varepsilon \in (0, 1/B)$. Then by Lemma 2.1 there exists a positive integer n_0 such that $(a, n)(b, n)/((a + b, n)(n - 1)!) > (1/B) - \varepsilon$, for all $n \geq n_0$. Hence,

$$F(a, b; a + b; x) \geq F_{n_0} + \left(\frac{1}{B} - \varepsilon\right) \sum_{n=n_0+1}^{\infty} \frac{x^n}{n} = F_{n_0} - \left(\frac{1}{B} - \varepsilon\right) (\log(1 - x) + S_{n_0}),$$

where

$$F_{n_0} = \sum_{n=1}^{n_0} \frac{(a, n)(b, n)}{(a + b, n)n!} x^n, \quad S_{n_0} = \sum_{n=1}^{n_0} \frac{x^n}{n}.$$

Dividing by $\log(1/(1 - x))$ and letting $x \rightarrow 1$, since $\varepsilon \in (0, 1/B)$ is arbitrary, we get

$$\liminf_{x \rightarrow 1} \frac{F(a, b; a + b; x)}{\log(1/(1 - x))} \geq \frac{1}{B},$$

so that the limit is $1/B$. \square

2.4. *Proof of Theorem 1.3.* (1) The limiting value as $x \rightarrow 0$ follows from series expansions, while the one as $x \rightarrow 1$ follows from Lemma 2.3. Next, let $g(x) = F(a, b; a + b; x) - 1$ and $h(x) = \log(1/(1 - x))$. Then $g(0) = h(0) = 0$, and by the monotone l'Hôpital rule [AVV4, Lemma 2.2] it is enough to show that $g'(x)/h'(x)$ is strictly increasing. Now [WW, p. 281]

$$\begin{aligned} \frac{g'(x)}{h'(x)} &= \frac{ab}{a + b} (1 - x) F(a + 1, b + 1; a + b + 1; x) \\ &= \frac{ab}{a + b} \left(1 + \sum_{n=0}^{\infty} \left(\frac{(a + 1, n + 1)(b + 1, n + 1)}{(a + b + 1, n + 1)(n + 1)!} \right. \right. \\ &\quad \left. \left. - \frac{(a + 1, n)(b + 1, n)}{(a + b + 1, n)n!} \right) x^{n+1} \right). \end{aligned}$$

The coefficient of x^{n+1} here is positive if and only if $(a + 1 + n)(b + 1 + n) > (a + b + n + 1)(n + 1)$, which holds if and only if $ab + (a + b)(n + 1) + (n + 1)^2 > (a + b)(n + 1) + (n + 1)^2$, which is true.

(2) The limiting values are clear from (1.6). Next, by series expansion,

$$g(x) - B = \sum_{n=1}^{\infty} \left(B \frac{(a, n)(b, n)}{(a + b, n)(n - 1)!} - 1 \right) \frac{x^n}{n},$$

so that all coefficients are negative by Lemma 2.1(4). \square

2.5. *Proof of Theorem 1.4.* For (1), let $g(x) = xF(a, b; c; x)$, $c = a + b$, and $h(x) = \log(1/(1 - x))$. Then $g(0) = h(0) = 0$ and

$$\begin{aligned} \frac{g'(x)}{h'(x)} &= (1 - x) \left(F(a, b; c; x) + \frac{abx}{c} F(a + 1, b + 1; c + 1; x) \right) \\ &= (1 - x) \left(\sum_{n=0}^{\infty} \frac{(a, n)(b, n)}{(c, n)} \frac{x^n}{n!} + \frac{ab}{c} \sum_{n=0}^{\infty} \frac{(a + 1, n)(b + 1, n)}{(c + 1, n)} \frac{x^{n+1}}{n!} \right) \\ &= (1 - x) \left(\sum_{n=0}^{\infty} \frac{(a, n)(b, n)}{(c, n)} \frac{x^n}{n!} + \sum_{n=0}^{\infty} \frac{(a, n + 1)(b, n + 1)}{(c, n + 1)} \frac{x^{n+1}}{n!} \right) \\ &= \sum_{n=0}^{\infty} \frac{(a, n)(b, n)}{(c, n)} \frac{x^n}{n!} + \sum_{n=0}^{\infty} \left(\frac{(a, n + 1)(b, n + 1)}{(c, n + 1)} - \frac{(a, n)(b, n)}{(c, n)} \right) \frac{x^{n+1}}{n!} \\ &\quad - \sum_{n=0}^{\infty} \frac{(a, n + 1)(b, n + 1)}{(c, n + 1)} \frac{x^{n+2}}{n!}. \end{aligned}$$

Hence

$$\begin{aligned} \frac{g'(x)}{h'(x)} - 1 &= \left(\frac{2ab}{c} - 1 \right) x + \sum_{n=0}^{\infty} \frac{(a, n + 2)(b, n + 2)}{(c, n + 2)} \frac{x^{n+2}}{(n + 2)!} \\ &\quad + \sum_{n=0}^{\infty} \frac{(a, n + 2)(b, n + 2)}{(c, n + 2)} \frac{x^{n+2}}{(n + 1)!} - \sum_{n=0}^{\infty} \frac{(a, n + 1)(b, n + 1)}{(c, n + 1)} \frac{x^{n+2}}{n!} \\ &\quad - \sum_{n=0}^{\infty} \frac{(a, n + 1)(b, n + 1)}{(c, n + 1)} \frac{x^{n+2}}{(n + 1)!} \\ &= \left(\frac{2ab}{c} - 1 \right) x + \sum_{n=0}^{\infty} \frac{(a, n + 1)(b, n + 1)}{(c, n + 2)(n + 2)!} \\ &\quad \times [(n + 1)(ab - 1) + (2ab - a - b)] x^{n+2}, \end{aligned}$$

in which all coefficients are negative. Thus $g'(x)/h'(x)$ is decreasing, hence so is $g(x)/h(x)$, by the monotone l'Hôpital rule [AVV4, Lemma 2.2], and (1) follows.

The proof for (2) is similar, except that all coefficients are positive.

Part (3) follows from (1.1) and the series for $\log(1/(1 - x))$.

(4) In the series expansion,

$$g_1(x) - (B - 1) = \sum_{n=1}^{\infty} \left(\frac{(a, n)(b, n)}{(a + b, n)n!} B - \frac{1}{n + 1} \right) x^n,$$

all coefficients are positive by Lemma 2.1(5).

(5) The proof is similar to (4), except that all coefficients are negative by Lemma 2.1(6). The limiting values are clear by (1.6). \square

2.6. **Lemma.** For $a, b \in (0, \infty)$, $n = 1, 2, 3, \dots$,

$$\sum_{k=0}^n \frac{(a, k)(b, k)}{(a+b, k)k!} > \frac{(a+1, n)(b+1, n)}{(a+b+1, n)n!} > \frac{(a, n)(b, n)}{(a+b, n)n!}.$$

Proof. The first inequality follows by induction, and the second one by the factorial property of (a, n) . \square

2.7. **Lemma.** For $a, b \in (0, \infty)$ and $x \in (0, 1)$ the Maclaurin series of the functions

$$\frac{1}{1-x} F(a, b; a+b; x) - F(a+1, b+1; a+b+1; x)$$

and

$$F(a+1, b+1; a+b+1; x) - F(a, b; a+b; x)$$

have constant term zero and all other coefficients strictly positive. In particular, these functions are increasing and convex on $(0, 1)$ and

$$F(a, b; a+b; x) < F(a+1, b+1; a+b+1; x) < \frac{1}{1-x} F(a, b; a+b; x)$$

for all $x \in (0, 1)$.

Proof. The results follow immediately from Lemma 2.6. \square

2.8. *Proof of Theorem 1.7.* The limiting value $f(0) = 1$ is obvious, while $f(1-) = 0$ follows from Theorem 1.3(1). Next, for each $x \in (0, 1)$ we have

$$4(1-x)^{-1/4} f'(x) = \frac{4ab}{a+b} F(a+1, b+1; a+b+1; x) - \frac{1}{1-x} F(a, b; a+b; x).$$

If $4ab \leq a+b$, then Lemma 2.7 implies that $f'(x) < 0$. Conversely, if f is decreasing, then $f'(x) \leq 0$ for all $x \in (0, 1)$, and letting x tend to 0 we get $4ab \leq a+b$. \square

The special case $a = b = \frac{1}{2}$ of Theorem 1.7 is well known. This special case follows, for instance, from the infinite product formulas for x'/\sqrt{x} and $(2/\pi)\sqrt{x}\mathcal{K}(x)$ in terms of the Jacobi nome $q = \exp(-\pi\mathcal{K}'/\mathcal{K})$ [WW, p. 488, Exercise 10] or from [AVV1, Theorem 2.2(3)].

2.9. *Remark.* It is easy to show that $(\sqrt{ab}, n)^2 \leq (a, n)(b, n) \leq ((a+b)/2, n)^2$ for all positive a, b and all $n = 1, 2, \dots$, with equality if and only if $a = b$. Thus

$$(2.10) \quad F(\sqrt{ab}, \sqrt{ab}; c; x) \leq F(a, b; c; x) \leq F((a+b)/2, (a+b)/2; c; x)$$

for $a, b, c > 0$, $x \in [0, 1)$, with equality if and only if $a = b$ or $x = 0$. Furthermore, for $a, c > 0$ and for $t \in (0, a)$ we see that $(a+t, n)(a-t, n)$ is a decreasing function of t on $[0, a]$ for $n = 1, 2, \dots$, so that

$$(2.11) \quad F(a+t_2, a-t_2; c; x) \leq F(a+t_1, a-t_1; c; x)$$

for $x \in (0, 1)$, $0 \leq t_1 < t_2 \leq a$. The second assertion of Lemma 2.7 also follows from the fact that $(a, n)(b, n)/(a+b, n)$, $a, b > 0$, is a strictly increasing function of a .

3. THE GAMMA FUNCTION

We next study some properties of the functions

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \quad \text{and} \quad \Psi(x) = \frac{d}{dx} \log \Gamma(x)$$

when x is real and positive.

3.1. Theorem. *The function $f(x) = x(\log x - \Psi(x))$ is decreasing and convex from $(0, \infty)$ onto $(\frac{1}{2}, 1)$.*

Proof. From [WW, p. 251, §12.32, Example] it follows that

$$f(x) = \frac{1}{2} + 2x \int_0^\infty \frac{t dt}{(t^2 + x^2)(e^{2\pi t} - 1)}.$$

Hence,

$$\begin{aligned} f'(x) &= 2 \int_0^\infty \frac{t dt}{(t^2 + x^2)(e^{2\pi t} - 1)} - 4x^2 \int_0^\infty \frac{t dt}{(t^2 + x^2)^2(e^{2\pi t} - 1)} \\ &= 2 \int_0^\infty \frac{t(t^2 - x^2) dt}{(t^2 + x^2)^2(e^{2\pi t} - 1)} \\ &= 2 \int_0^x \frac{t}{e^{2\pi t} - 1} \frac{(t^2 - x^2) dt}{(t^2 + x^2)^2} + 2 \int_x^\infty \frac{t}{e^{2\pi t} - 1} \frac{(t^2 - x^2) dt}{(t^2 + x^2)^2}. \end{aligned}$$

Since $t/(e^{2\pi t} - 1)$ is decreasing on $(0, \infty)$, we get

$$f'(x) < \frac{2x}{e^{2\pi x} - 1} \int_0^\infty \frac{(t^2 - x^2) dt}{(t^2 + x^2)^2}.$$

Substituting $t = x \tan u$, we get

$$\int_0^\infty \frac{(t^2 - x^2) dt}{(t^2 + x^2)^2} = \frac{1}{x} \int_0^{\pi/2} (\sin^2 u - \cos^2 u) du = 0.$$

Thus we have shown that $f(x)$ is strictly decreasing, so that $f(0+)$ exists. To obtain this limit we observe first that $t/(e^{2\pi t} - 1) < 1/(2\pi)$ implies that

$$\lim_{x \rightarrow 0+} 2x \int_0^\infty \frac{t dt}{(t^2 + x^2)(e^{2\pi t} - 1)} \leq \frac{1}{2}.$$

Next, fix $\varepsilon \in (0, 1/(2\pi))$. Since $\lim_{t \rightarrow 0+} t/(e^{2\pi t} - 1) = 1/(2\pi)$, there exists $\delta > 0$ such that $t/(e^{2\pi t} - 1) > 1/(2\pi) - \varepsilon$ for all $t \in (0, \delta)$. Thus

$$2x \int_0^\infty \frac{t dt}{(t^2 + x^2)(e^{2\pi t} - 1)} > 2x \left(\frac{1}{2\pi} - \varepsilon \right) \int_0^\delta \frac{dt}{t^2 + x^2} = 2 \left(\frac{1}{2\pi} - \varepsilon \right) \arctan \frac{\delta}{x}.$$

Now letting first x , then ε , tend to zero gives

$$\lim_{x \rightarrow 0+} 2x \int_0^\infty \frac{t dt}{(t^2 + x^2)(e^{2\pi t} - 1)} \geq \frac{1}{2}.$$

For $0 \leq a < b \leq \infty$ denote

$$I(a, b) = \int_a^b \frac{t dt}{(t^2 + x^2)(e^{2\pi t} - 1)}.$$

Then, since $t/(e^{2\pi t} - 1) \leq 1/(2\pi)$,

$$2xI(0, 1) \leq \frac{1}{\pi} \arctan \frac{1}{x},$$

while

$$\begin{aligned} I(1, \infty) &\leq \frac{1}{1+x^2} \int_1^\infty \frac{t dt}{e^{2\pi t} - 1} = \frac{1}{1+x^2} \int_1^\infty \frac{te^{-\pi t} dt}{2 \sinh(\pi t)} \\ &\leq \frac{1}{2\pi(1+x^2)} \int_1^\infty e^{-\pi t} dt = \frac{1}{2\pi^2(1+x^2)}. \end{aligned}$$

Hence $\lim_{x \rightarrow \infty} f(x) = \frac{1}{2}$.

To prove the convexity, let $J[g]$ denote the integral of a function g from 0 to ∞ . Then, as above, $f'(x) = 2J[g(t)h(t, x)]$, where

$$g(t) = t/(e^{2\pi t} - 1) \quad \text{and} \quad h(t, x) = (t^2 - x^2)/(t^2 + x^2)^2.$$

Hence,

$$f''(x) = 4xJ[g(t)H(t, x)], \quad \text{where} \quad H(t, x) = \frac{\partial h(t, x)}{\partial x} = \frac{x^2 - 3t^2}{(t^2 + x^2)^3}.$$

Since $g(t)$ is decreasing, by splitting the integral on $(0, \infty)$ into the sum of an integral on $(0, x/\sqrt{3})$ and one on $(x/\sqrt{3}, \infty)$, we get

$$f''(x) > 4xg(x/\sqrt{3})J[H(t, x)].$$

Now substituting $t = x \tan u$, we see that $J[H(t, x)] = 0$. Hence $f''(x) > 0$ on $(0, \infty)$, so that f is convex on $(0, \infty)$. \square

3.2. Theorem. (1) *The function $f_1(x) = x^{1/2-x}e^x\Gamma(x)$ is decreasing and log-convex from $(0, \infty)$ onto $(\sqrt{2\pi}, \infty)$.*

(2) *The function $f_2(x) = x^{1-x}e^x\Gamma(x)$ is increasing and log-concave from $(0, \infty)$ onto $(1, \infty)$.*

Proof. (1) The limiting value at 0 follows from the relation $\Gamma(x+1) = x\Gamma(x)$, while the one at ∞ follows from Stirling's formula. Next,

$$-x \frac{d}{dx} \log f_1(x) = f(x) - \frac{1}{2},$$

where $f(x)$ is as in Theorem 3.1, is clearly positive and decreasing.

(2) The limiting value at 0 follows from the relation $\Gamma(x+1) = x\Gamma(x)$, while the one at ∞ follows from Stirling's formula. Next,

$$-x \frac{d}{dx} \log f_2(x) = 1 - f(x) > 0,$$

where $f(x)$ is as in Theorem 3.1. Moreover, by the monotone l'Hôpital rule [AVV4, §2], it follows that $\frac{d}{dx} \log f_2(x)$ is decreasing. \square

3.3. Remark. A result similar to Theorem 3.2 appears in [Lu, p. 17], whereas in [Mi, 3.6.55, p. 288] a version of Theorem 3.1 is given. In [G, p. 283] it is

shown that $x\Psi(x)$ is convex for $x > 0$. For some recent results on the gamma function see [A1].

4. REFINEMENTS

A problem of interest is to obtain upper estimates for the complete elliptic integral

$$\frac{2}{\pi} \mathcal{K}(x') = F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^2\right)$$

in terms of variants of the type

$$F\left(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^3\right)$$

for $x \in (0, 1)$ and $\delta \in (0, \frac{1}{2})$. Observe initially that the inequality

$$(4.1) \quad F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^2\right) < F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^3\right)$$

for $x \in (0, 1)$ follows immediately from the monotonicity of $F(\frac{1}{2}, \frac{1}{2}; 1; x)$ as a function of x . We seek a refinement of (4.1).

J. Borwein and P. Borwein [BB2, (2.9)] have shown that

$$(4.2) \quad F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^2\right) < F\left(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^3\right)$$

for $\delta = \frac{1}{6}$ and for all $x \in (0, 1)$. It has been conjectured recently [AVV3, p. 79] that (4.2) holds for all $\delta \in (0, \frac{1}{6})$ and for all $x \in (0, 1)$. We next obtain a refinement of (4.2), which also proves the statement of Theorem 1.9.

4.3. **Theorem.** *Let $x \in (0, 1)$, $c, d \in (0, \infty)$, $4c < \pi d$. Then*

$$(4.4) \quad F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^c\right) < F\left(\frac{1}{2} - \delta_0, \frac{1}{2} + \delta_0; 1; 1 - x^d\right)$$

$$(4.5) \quad < F\left(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^d\right)$$

$$(4.6) \quad < F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^d\right)$$

for all $\delta \in (0, \delta_0)$, where $\delta_0 = ((d\pi - 4c)/(4\pi d))^{1/2}$.

Proof. Let $f_\delta(x)$ be defined by

$$(4.7) \quad f_\delta(x) = \frac{1 - F(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; x)}{\log(1 - x)}.$$

It follows from Theorem 1.3 that, for all $x \in (0, 1)$ and $\delta \in [0, \frac{1}{2})$,

$$(4.8) \quad \left(\frac{1}{2} - \delta\right) \left(\frac{1}{2} + \delta\right) < f_\delta(x) < \frac{1}{B(\frac{1}{2} - \delta, \frac{1}{2} + \delta)},$$

where $B(a, b)$ is the Euler beta function. From the reflection formula $\Gamma(a)\Gamma(1 - a) = \pi/\sin(a\pi)$ [AS, p. 256], it follows that

$$(4.9) \quad \frac{1}{4} - \delta^2 < f_\delta(x) < \frac{1}{\pi} \sin\left(\left(\frac{1}{2} - \delta\right)\pi\right)$$

for all $x \in (0, 1)$ and $\delta \in [0, \frac{1}{2}]$. From (4.9) with $\delta = 0$ it follows that

$$\frac{F(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^c) - 1}{\log(1/x^c)} = f_0(1 - x^c) < \frac{1}{\pi}.$$

Again applying (4.9) with $\delta \in (0, \delta_0)$ yields

$$\begin{aligned} \frac{F(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^d) - 1}{\log(1/x^d)} &= \frac{d}{c} \left[\frac{F(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^d) - 1}{\log(1/x^d)} \right] \\ &= \frac{d}{c} f_\delta(1 - x^d) > \frac{d}{c} \left(\frac{1}{4} - \delta^2 \right) \\ &> \frac{d}{c} \left(\frac{1}{4} - \delta_0^2 \right) = \frac{1}{\pi}. \end{aligned}$$

Therefore, for $0 < \delta \leq \delta_0$ and $x \in (0, 1)$,

$$\begin{aligned} F\left(\frac{1}{2}, \frac{1}{2}; 1; 1 - x^c\right) &= 1 + f_0(1 - x^c) \log \frac{1}{x^c} \\ &< 1 + \frac{1}{\pi} \log \frac{1}{x^c} \\ &< 1 + \frac{d}{c} f_\delta(1 - x^d) \log \frac{1}{x^c} \\ &= F\left(\frac{1}{2} - \delta, \frac{1}{2} + \delta; 1; 1 - x^d\right), \end{aligned}$$

which establishes (4.4). Inequalities (4.5) and (4.6) are immediate consequences of (2.11). \square

4.10. *Conjectures.* (1) For $c = 2, d = 3$ the best possible value of δ_0 for which Theorem 4.3 is valid is $\delta_0 = (\pi - 2 \arcsin(2/3))/(2\pi) \approx 0.268$ (see [AVV3, p. 6]).

(2) Theorem 1.4 has a counterpart for the generalized hypergeometric function ${}_pF_q(a_1, \dots, a_p; b_1, \dots, b_q; x)$ for the case $a_i > 0, b_j > 0, p = q + 1$, when the sum is zero-balanced, i.e. when $\sum_{i=1}^p a_i = \sum_{j=1}^q b_j$. See also [B, p. 152].

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