Title	A Diophantine equation arising from tight 4-designs
Author(s)	Bremner, Andrew
Citation	Osaka Journal of Mathematics. 16(2) P.353-P.356
Issue Date	1979
Text Version	publisher
URL	https://doi.org/10.18910/8744
DOI	10.18910/8744
rights	
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Bremner, A.
Osaka J. Math.
16 (1979), 353-356

A DIOPHANTINE EQUATION ARISING FROM TIGHT 4-DESIGNS

ANDREW BREMNER

(Received July 5, 1978)

Ito [1,2] and Enomoto, Ito, Noda [3] show that there exist only finitely many tight 4-designs, by proving that such a design gives rise to a unique rational integral solution of the diophantine equation

$$(2y^2-3)^2 = x^2(3x^2-2) \tag{1}$$

and then invoking a result of Mordell [4] to say that this equation has only finitely many solutions in integers x,y. A privately communicated conjecture is that (1) has only the 'obvious' solutions $(\pm x, \pm y)=(1,1), (3,3)$, with the implication that the only tight 4-designs are the Witt designs. We show here that this is indeed the case.

We are exclusively interested in integral points on the curve (1), which is a lightly disguised elliptic curve; standard arguments show that the group of rational points has one generator of infinite order which may be taken to be (3,3).

Suppose now that x, y are integers satisfying (1). Then there is an integer w with

$$\begin{aligned} 3x^2-2 &= w^2 \\ 2y^2-3 &= wx\,. \end{aligned} \tag{2}$$

Clearly x,w,y are odd. Following Cassels [5] we write (2), in virtue of the identity $w^2-3x^2+2wx\sqrt{-3}=(w+x\sqrt{-3})^2$, in the form

$$\left(\frac{w+x\sqrt{-3}}{2}\right)^2-y^2\sqrt{-3} = \frac{-1-3\sqrt{-3}}{2} \tag{3}$$

We now work in the algebraic number field $Q(\theta)$ where $\theta^2=\sqrt{-3}$. It is easy to check that the ring of integers of $Q(\theta)$ has $\boldsymbol{Z}$-basis $\left\{1, \theta, \frac{1+\theta^2}{2}, \frac{\theta+\theta^3}{2}\right\}$, that the class-number is 1, and that the group of units is generated by $\{-\omega, \omega+\theta\}$ where $\omega=\dfrac{-1-\theta^2}{2}$ is a cube root of unity. The relative norm to $Q(\sqrt{-3})$ of the fundamental unit $\varepsilon=\omega+\theta$, is ω.

Further, $\frac{-1-3\sqrt{-3}}{2}$ is prime in $\boldsymbol{Z}[\omega]$, and splits into two first degree primes in $Q(\theta)$:

$$\frac{-1-3\sqrt{-3}}{2}=(1-\tfrac{1}{2}\theta-\theta^2-\tfrac{1}{2}\theta^3)(1+\tfrac{1}{2}\theta-\theta^2+\tfrac{1}{2}\theta^3)\,.$$

Now the left hand side of (3) is the product of the two factors $\frac{w-x\sqrt{-3}}{2}\pm y\theta$ conjugate over $Q(\sqrt{-3})$, so by unique factorisation we deduce that

$$\frac{w+x\theta^2}{2}+y\theta=\eta(1-\theta^2\pm\tfrac{1}{2}\theta(1+\theta^2))$$

where η is a unit of $Q(\theta)$ with relative norm 1 - the possibilities for η are $\pm\varepsilon^{3m}$, $\pm\omega\varepsilon^{3m+1}$, $\pm\omega^2\varepsilon^{3m+2}$, for some integer m. By changing the sign of y if necessary, we may thus assume that

$$\pm\left(\frac{w+x\theta^2}{2}+y\theta\right)=(\omega\varepsilon)^i(1+\tfrac{1}{2}\theta-\theta^2+\tfrac{1}{2}\theta^3)E^m \tag{4}$$

where $i=0,1,2$ and $E=\varepsilon^3=\frac{1}{2}(11-3\theta-3\theta^2+5\theta^3)$.

Write (4) as

$$\pm\left(\frac{w+x\theta^2}{2}+y\theta\right)=\lambda E^m$$

where λ is one of three possibilities,

$$\lambda_1=1+\frac{1}{2}\theta-\theta^2+\frac{1}{2}\theta^3$$

$$\lambda_2=\frac{5}{2}-3\theta+\frac{3}{2}\theta^2$$

$$\lambda_3=-8+\frac{5}{2}\theta+2\theta^2-\frac{7}{2}\theta^3\,.$$

We now choose to work 37-adically.

Since $E^6\equiv-1 \bmod 37$, we have upon putting $m=6n+r$, $0\le r\le 5$,

$$\pm\left(\frac{w+x\theta^2}{2}+y\theta\right)=\lambda E^r(-1-37\xi)^n$$

where ξ is an integer of $Q(\theta)$ which by direct calculation satisfies $\xi\equiv-15\theta-5\theta^3$ mod 37.

Accordingly, we require that the coefficient of $\frac{\theta+\theta^3}{2}$ in λE^r be congruent to zero modulo 37: and this is clearly equivalent to the coefficient of θ^3 being zero modulo 37.

From the following table we deduce that λE^r can only be λ_2 or $\lambda_3 E^{-1}$ (absorbing an E^6 into E^{6n} for convenience) where $\lambda_3 E^{-1} = -\frac{1}{2} + \theta + \frac{1}{2}\theta^2$. Coefficient modulo 37 of θ^3 in $\lambda_i E^r$:-

	$r=0$	1	2	3	4	5
$\lambda_1 E^r$	19	6	14	13	1	2
$\lambda_2 E^r$	0	27	3	30	27	18
$\lambda_3 E^r$	15	28	12	20	18	0

In the case that $\lambda = \lambda_2$we have

$$\pm\left(\frac{w+x\theta^2}{2} + y\theta\right) = \left(\frac{5}{2} - 3\theta + \frac{3}{2}\theta^2\right)(1+37\xi)^n \tag{5}$$

One can treat this exponential equation in the manner of Skolem [6], but it is preferable to argue directly. Suppose in (5) that $n \neq 0$, and let the highest power of 37 that divides n, be s.

$$\begin{aligned} \text{Now}\quad (1+37\xi)^n &= 1 + 37n\xi + 37^2\tbinom{n}{2}\xi^2 + \cdots \\ &\equiv 1 + 37n\xi \mod 37^{s+2} \\ &\equiv 1 + 37n(-15\theta - 5\theta^3) \mod 37^{s+2}. \end{aligned}$$

So equating to zero the coefficient of θ^3 on the right hand side of (5) we obtain

$$0 \equiv \frac{5}{2}(-5n.37) + \frac{3}{2}(-15n.37) \mod 37^{s+2}$$

$$\text{i.e. } 0 \equiv -35n.37 \mod 37^{s+2}, \text{ contradiction.}$$

Hence $n=0$ is the only possibility for a solution in (5), and it does indeed result in $(x,y)=(3,-3)$.

The case $\lambda = \lambda_3 E^{-1}$ is treated in precisely the same way, resulting in the single solution $(x,y)=(1,1)$.

We have thus shown that the only integer solutions of (1) are indeed given by $(\pm x, \pm y) = (1,1), (3,3)$.

EMMANUEL COLLEGE, CAMBRIDGE

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