Hyperkähler quotients and algebraic curves

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Abstract: We develop a graphical representation of polynomial invariants of unitary gauge groups, and use it to find the algebraic curve corresponding to a hyperkähler quotient of a linear space. We apply this method to four dimensional ALE spaces, and for the $A_k$, $D_k$, and $E_6$ cases, derive the explicit relation between the deformations of the curves away from the orbifold limit and the Fayet-Iliopoulos parameters in the corresponding quotient construction. We work out the orbifold limit of $E_7$, $E_8$, and some higher dimensional examples.

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1. Introduction

The two dual descriptions of D-branes as gravitational solitons of supergravity theories and as objects on which open strings can end make it possible to derive interesting new relations between gauge theories and gravity/string-theory. A celebrated example of this is the Maldacena conjecture [1]. To generalize the Maldacena conjecture to cases with more complicated gauge groups and matter content, as well as to cases with less supersymmetry, it is useful to study D-branes sitting on various spacetime singularities [2,3,4,5].

This method was pioneered in [6], where D-branes on orbifold singularities of the type $C^2/Z_k$ were studied. It was shown that the gauge theory realized on the brane is conveniently summarized by a “quiver diagram” from which one can read off the gauge group structure and the matter content. The orbifolds studied in that paper gave rise to quiver diagrams corresponding to the (extended) $A_k$ Dynkin diagram; the generalization to the $D$ and $E$ series, corresponding to non-abelian orbifolds, was given in [7]. In this picture, the Fayet-Iliopoulos terms in the gauge theory are related to twisted sector moduli of the orbifold, so that turning them on corresponds to blowing up the orbifold singularity.

More complicated orbifolds preserving less supersymmetry were studied in, e.g., [8,9].

A complementary picture of the same models can be found using T-duality: the singularity generically transforms into a web of NS-branes [10] and the D-branes change their dimension to give configurations of the Hanany-Witten type [11]. In this dual picture, many features of the model become geometric. In particular, the Fayet-Iliopoulos terms are interpreted as various distances between branes. In many ways this dual picture is complementary to the original picture in that different things become easy to see whereas others, simple in the original picture, become harder to deal with in the T-dual version of the model. This T-duality has been studied in detail for the A-series [12] and the D-series [13,14] but no duals have yet been found for the E-series.

One aim of this paper is to provide guidance to finding such a correspondence by constructing the map between the Fayet-Iliopoulos parameters, corresponding to the positions of various branes, and the deformations of the curve. In this paper, we find the algebraic curve corresponding to any manifold that is a hyperkähler quotient [15,16] of a linear space. Such a quotient may be described in terms of a quiver diagram [6]. The cases when it yields a four-dimensional ALE manifold have been analyzed and have an A-D-E classification [17,18]. In particular we include the Fayet-Iliopoulos parameters in the calculation of the curve for the $A_k$, $D_k$ and $E_6$ cases. Remarkably we find that the
curve in the $E_6$ case is identical to the Seiberg-Witten curve for certain $N = 2$ superconformal Yang-Mills theories with $E_6$ global symmetry and with the Fayet-Iliopoulos terms playing the roles of chiral superfield VEV’s. It would be interesting if some duality or mirror symmetry were responsible for this apparent coincidence.

The paper is organized as follows. In section 2 we review the hyperkähler quotient in $N = 1$ superspace \[15,16\]. In section 3, we describe the algebraic curves of these spaces, and derive them from the $N = 1$ superspace description of the hyperkähler quotient for the $A_k$ \[19\], $D_k$ \[20\], and $E_k$ cases. In section 4, we discuss a number of issues and consider some higher dimensional examples outside the A-D-E classification.

2. Hyperkähler quotients

The hyperkähler quotient was introduced in \[15\] and was given a full mathematically rigorous presentation in \[16\]. It arises naturally when one gauges isometries of a nonlinear $\sigma$-model \[21\] in such a way as to preserve four dimensional $N = 2$ supersymmetry. In components ($N = 0$), it is the quotient of a constrained submanifold (the zero-set of the moment map \[16\]) by some real compact gauge group. In $N = 1$ superspace, the vector multiplet relaxes a part of the constraints, leaving only a holomorphic constraint, and enhances the gauge group to its complexification (subtleties pertaining to quotients by noncompact groups are discussed in \[16\], p. 548).

Explicitly, we want to consider the hyperkähler quotient construction of 4-dimensional ALE spaces \[18\]. We start with a quaternionic vector space that we describe as an even dimensional complex space with $n$ pairs of coordinates $(z_+, z_-)$. In the language of supersymmetry, each pair of complex coordinates is called a hypermultiplet, and in $N = 1$ superspace, these are pairs of chiral superfields. The Kähler potential of the metric is the superspace Lagrangian \[22\]. The holomorphic moment map constraints take the form \[15\]

$$z_+ T_A z_- = \chi(T_A), \quad (2.1)$$

where the $T_A$ are generators of the gauge group (taken to be hermitian), and $\chi$ is an arbitrary character–i.e., a linear combination of the $U(1)$ factors of the group:

$$z_+ T_A z_- = 0 \quad A \notin \text{any } U(1)$$

$$= b_A \quad A \in \text{any } U(1). \quad (2.2)$$
In superspace, these are called Fayet-Iliopoulos terms. The Kähler potential of the quotient space is found by solving a set of real equations for the $N = 1$ vector superfields $V^A$ \[(2.3)\] 
and substituting the solution into the gauged flat space Kähler potential of the $z_\pm$'s \[(2.4)\] where $\hat{\chi}$ is an independent character. The particular choices of gauge groups and representations are given in \[18\]; for a review see \[19\]. A summary is given in table 1:

Table 1

In the table, each hyperkähler quotient by a product gauge group $U(N_1) \times \cdots \times U(N_k)$ is represented as an extended Dynkin diagram for the A-D-E series of Lie groups; the $i$'th simple root, which has a label $N_i$ in the Dynkin diagram, corresponds to a factor $U(N_i)$ in the gauge group and each link between two roots $i, j$ corresponds to a hypermultiplet in the $(N_i, \bar{N}_j)$ representation\[3\].

3. Algebraic curves

As stated above, four dimensional ALE hyperkähler manifolds are classified by the extended Dynkin diagrams corresponding to the A-D-E Lie groups \[17\]. As complex manifolds, they can be described by holomorphic curves in $C^3$ with coordinates $X, Y, Z$. The

\[1\] As the chiral superfields $z_\pm$ that make up the hypermultiplet are always in conjugate representations, the orientation of the links does not matter.
curves have a leading piece corresponding to the orbifold limit of the spaces, and deformation parameters corresponding to the character (Fayet-Iliopoulos) terms of the quotient construction. The curves are summarized in table 2:

| Classification | Polynomial | Deformations |
|----------------|------------|--------------|
| $A_k$          | $XY - Z^{k+1}$ | $1, \ldots, Z^{k-1}$ |
| $D_k$          | $X^2 + Y^2Z - Z^{k-1}$ | $1, Y, Z, \ldots, Z^{k-2}$ |
| $E_6$          | $X^2 + Y^3 - Z^4$ | $1, Y, Z, YZ, Z^2, YZ^2$ |
| $E_7$          | $X^2 + Y^3 + YZ^3$ | $1, Y, Y^2, Z, YZ, Z^2, Y^2Z$ |
| $E_8$          | $X^2 + Y^3 + Z^5$ | $1, Y, Z, YZ, Z^2, Z^3, YZ^2, YZ^3$ |

Table 2

The curve corresponding to a given hyperkähler quotient can be constructed by finding all the (gauge group) invariant holomorphic polynomials modulo the holomorphic constraints (2.2); for the A-D-E spaces, we find exactly three polynomials that satisfy an algebraic constraint, which, after suitable redefinitions is precisely the equation of the corresponding algebraic curve. The construction is in the spirit of Seiberg’s construction of effective superpotentials [23].

We now describe the actual calculations. To find the correct variables and derive the curve it is useful to employ the following graphic “bug calculus”.

As described above, we can represent any hyperkähler quotient by a product gauge group $U(N_1) \times \ldots \times U(N_k)$ as a quiver diagram where the $i$'th node, labeled $N_i$, corresponds to a $U(N_i)$ gauge group and each link (including orientation) between two nodes $i, j$ corresponds to a hypermultiplet in the $(N_i, \bar{N}_j)$ representation. It is therefore natural to represent any invariant that can be obtained by multiplying the chiral fields of the model as a closed oriented loop in the quiver diagram.

The holomorphic constraints (2.2) can be represented in bug calculus. Each gauge group (i.e., node) has its own constraint. For an “endpoint” the constraint is shown in Figure 1a and for a point in a chain the constraint is shown in Figure 1b. For more complicated junctions one generalizes this keeping in mind that the sign of each term is

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2 A quiver diagram is essentially a Dynkin diagram with arrows on the links indicating an orientation; when we construct invariant polynomials, we need to keep track of the orientation.
Figure 1: The bug calculus. $b_i$ is the Fayet-Iliopoulos parameter associated to the $i$’th node, and a vertical bar through the $i$’th node represents a $U(N_i)$ Kronecker-$\delta$.

determined by the orientation of the link it sits on. This is shown for two of the junctions that appear in this paper: the three and four-point vertices in Figures 1c and 1d.

A second important ingredient is the so-called Schouten identity. This allows us to untwist various loops showing that complicated variables can be written as products of simpler ones. They are derived by observing that the totally antisymmetric product of $n+1$ $n$-dimensional indices is identically zero. The simplest identity holds for one dimensional matrices and simply says that one dimensional matrices commute. Graphically this means that on any node representing a $U(1)$ gauge group we are allowed to split the lines and reconnect them in any way as long as we respect the orientation of the loops.

The Schouten identity for two dimensional matrices looks slightly more complicated. It can be derived from

$$M_{k_1}^{i_1} N_{k_2}^{i_2} K_{k_3}^{i_3} = 0.$$  (3.1)
If we contract the indices we can derive the following identity appropriate for our purposes

$$\text{Tr}(\{M, N\} K) = \text{Tr}(MN)\text{Tr}(K) + \text{Tr}(MK)\text{Tr}(N) + \text{Tr}(NK)\text{Tr}(M) - \text{Tr}(M)\text{Tr}(N)\text{Tr}(K).$$

(3.2)

In principle we could also implement this identity graphically. However, in practice it is easier to use it in algebraic form and then to go on and use the graphic methods on each term separately.

These are all the tools we need to derive the algebraic curve for any hyperkähler quotient corresponding to an arbitrary quiver diagram: we draw closed loops of increasing order in the number of links, and use the bug calculus to find the independent nonvanishing invariants. In practice, we first consider the orbifold limit, as then the relations between the invariants are simpler; the final calculations away from this limit then follow precisely the same route, but yield many more terms. The independent invariants are good coordinates on the moduli space. When we find no new independent invariants, we have all the coordinates of the moduli space. To find the algebraic curve, we consider the product of the highest order invariant with its orientation reversed image and use Schouten identities to express it as a product of lower invariants; for the $D_k$ and $E_k$ but not the $A_k$ cases, the orientation reversed loop is proportional to the original invariant plus algebraic functions of the lower invariants. For the $A_k$ and $D_k$ cases, the $U(1)$ Schouten identity is all we need.

We illustrate the method with two examples: $A_3$ and $D_4$, and then describe our results for the general case. Figure 2 describes the full calculation for $A_3$: 2a) shows the quiver diagram, 2b) defines two of the independent variables, $X, Y$, 2c) defines the variable $Z$ and uses the relation 1b) to express other similar diagrams in terms of it (note that the Fayet-Iliopoulos terms satisfy $\sum_{1}^{4} b_i = 0$), and finally, using the relation in 2c), 2d) gives the algebraic curve in diagramatic form.

$$XY = Z(Z - b_1)(Z - b_1 - b_2)(Z - b_1 - b_2 - b_3)$$

(3.3)

The calculation for the general $A_k$ is completely analogous, and gives the curve $XY = \prod_{i=0}^{k} (Z - \sum_{j=1}^{i} b_j)$, where again $\sum_{1}^{k+1} b_i = 0$.

Figures 3 and 4 describe the calculation for $D_4$. Figure 3a) shows the quiver diagram, Figure 3b) defines the three independent variables and Figures 3c) and 3d) give the

$^3$ This can be made to match the curve given in table 2 by shifting $Z \rightarrow Z + \frac{1}{4}(3b_1 + 2b_2 + b_3)$. 
Figure 2: Diagramatic representation of the $A_3$ invariants, moment map constraints, and algebraic curve.

constraints 1c) and 1d) for this particular case; as for the $A_k$ case, the Fayet-Iliopoulos coefficients are constrained: $\sum_1^4 b_i = 2b_5$.

Figure 4a) expresses a four-link diagram in terms of the basic four-link diagrams $W$ and $V$. Figures 4b) and 4c) relate $U$ to its orientation reversed image. Figure 4d) yields the algebraic curve in diagramatic form. Substituting 4a)-c) and similar relations into 4d) we find

$$U^2 + U[(b_4 - b_1)V + (b_4 - b_2)W + a_1] - W^2V - WV^2 + a_2WV = 0 ,$$

where

$$a_1 \equiv b_4(b_5 - b_4)(b_5 - b_4 - b_3) , \quad a_2 \equiv \frac{1}{2} \left[ \sum_{i \neq 3}^4 b_i(b_5 - b_i) - b_3(b_5 - b_3) \right] .$$
Making the following redefinitions,
\[
U = \frac{1}{2}[X + (b_1 - b_4)V + (b_2 - b_4)W - a_1],
V = \frac{1}{2}[Y - W + a_2 - \frac{1}{2}(b_1 - b_4)(b_2 - \frac{1}{2}(b_1 + b_4))],
W = -Z - \frac{1}{4}(b_1 - b_4)^2,
\]
we find a standard form of the algebraic curve for $D_4$:
\[
X^2 + Y^2Z - Z^3 + \alpha_0 Y - \sum_{i=1}^{3} \alpha_i Z^{i-1} = 0.
\]

The coefficients $\alpha_i$ are expressed in terms of the Fayet-Iliopoulos parameters $b_i$ as follows:
\[
\begin{align*}
\alpha_0 &= \frac{1}{8}(b_1^2 - b_4^2)(b_2^2 - b_3^2), \\
\alpha_1 &= \frac{1}{32}[(b_1^2 + b_4^2)(b_2^2 - b_3^2)^2 + (b_2^2 + b_3^2)(b_1^2 - b_4^2)^2], \\
\alpha_2 &= \frac{1}{16}[(b_1^2 - b_4^2)^2 + (b_2^2 - b_3^2)^2 + 4(b_1^2 + b_4^2)(b_2^2 + b_3^2)], \\
\alpha_3 &= \frac{1}{2} \sum_{i=1}^{4} b_i^2.
\end{align*}
\]
For the general $D_k$, we label the nodes as indicated in Figure 5a); the basic variables $U, V, W$ are defined by analogy to the $D_4$ case (Figure 3b), and are shown in Figure 5b). The Fayet-Iliopoulou coefficients $b_i$ (associated to the $i$’th node) satisfy the constraint

$$\sum_{i=1}^{4} b_i = 2 \sum_{i=5}^{k+1} b_i .$$  \tag{3.9}$$

We express the curve in terms of certain polynomials in $W$ that we define recursively as follows:

$$s_i = \left[ b_1 + b_4 - b_{i+3} - 2\beta_{i-2} \right] s_{i-1} + \left[ s_1 - (b_1 - \beta_{i-2})(b_4 - \beta_{i-2}) \right] s_{i-2} ,$$

$$t_i = \left[ b_1 + b_4 + b_{k+3-i} - 2\beta_{k-1-i} \right] t_{i-1} + \left[ s_1 - (b_1 - \beta_{k-1-i})(b_4 - \beta_{k-1-i}) \right] t_{i-2} ,$$

$$\beta_i \equiv \sum_{j=5}^{i+4} b_j ;$$

their graphical expression is given in Figure 5c). The initial conditions are

$$s_0 = t_0 = 0 , \quad s_1 = W , \quad t_1 = W + \beta_{k-3}(\beta_{k-3} - b_1 - b_4) + \frac{1}{2}(b_1^2 + b_4^2 - b_2^2 - b_3^2) .$$  \tag{3.11}$$

\textbf{Figure 4:} Some typical calculations for the $D_4$ example.
Figure 5: The basic invariants for $D_k$ and some other useful invariant quantities.

For arbitrary $k$, the curve in the form analogous to (3.4) is

$$U^2 - WV^2 + U[P(W) + (b_4 - b_1)V] + VQ(W) = 0,$$

where $P$ and $Q$ are polynomials of order $O(W^{[\frac{k-3}{2}] + 1})$ and $O(W^{[\frac{k-2}{2}] + 1})$, respectively:

$$P = \frac{b_3 - b_2}{t_1}(t_{k-1} - b_1t_{k-2}) + s_{k-2} - \frac{b_1 + b_3 - \beta_{k-3}}{s_1}[s_{k-1} - (b_1 - \beta_{k-3})s_{k-2}],$$

$$Q = -\frac{s_1}{t_1}[t_{k-1} + (b_3 - \beta_{k-3})t_{k-2}].$$

Though they do not have a graphical representation, $s_i, t_i$ for $i > k - 3$ are defined by the recursion relations (3.10); we also need $b_i = 0$ for $i > k + 1$, $\beta_i = 0$ for $i < 1$, and we take $b_{k+3-i} = 0$, and not $b_4$, for $i = k - 1$. Because of the initial conditions (3.11), $s_i/s_1$ and $t_i/t_1$ are polynomials in $W$. 
The curve (3.12) can be put into the standard form by redefinitions analogous to (3.6):

\[
U = \frac{1}{2} \left[ X + (b_1 - b_4) V - P(W) \right] , \\
V = \frac{1}{2} \left[ Y - \frac{R(Z) - R(0)}{Z} \right] , \\
W = -Z - \frac{1}{4} (b_1 - b_4)^2 , \\
R(Z) \equiv \left[ Q(W(Z)) + \frac{1}{2} (b_1 - b_4) P(W(Z)) \right] W(Z) = -Z - \frac{1}{4} (b_1 - b_4)^2 ,
\]

which gives

\[
X^2 + Y^2 Z + 2R(0)Y - \left[ \frac{R^2(Z) - R^2(0)}{Z} + P^2(W(Z)) \right] = 0 .
\] (3.15)

Calculating the first six examples, we are able to rewrite the curve (3.13) explicitly in terms of the Fayet-Iliopoulos coefficients:

\[
X^2 + Y^2 Z - 2Y \prod_{i=1}^{k} B_i - \frac{\prod_{i=1}^{k} (Z + B_i^2) - \prod_{i=1}^{k} B_i^2}{Z} = 0 ,
\] (3.16)

where

\[
\{ B_i \} \equiv \left\{ \frac{1}{2} (b_1 - b_4), \frac{1}{2} (b_2 - b_3), \frac{1}{2} (b_1 + b_4), \frac{1}{2} (b_1 + b_4) - \sum_{i=5}^{k} b_i \right\} .
\] (3.17)

In the orbifold limit, \( B_i = 0 \) which agrees with the entry for \( D_k \) in table 2. After completing our calculation, we realized that the same expression for the deformation in terms of the Fayet-Iliopoulos parameters had been deduced by completely different methods in [20].

We note that the quantities that enter in both the \( A_k \) and the \( D_k \) cases are related to the weights of the fundamental representation of the Lie algebra in question. If we think of each Fayet-Iliopoulos parameter as the simple root associated to its node in the Dynkin diagram, then the expressions that occur (\( \sum_{j=1}^{i} b_j \) in the \( A_k \) case and the \( B_i \) (3.17) in the \( D_k \) case) are the weights of the fundamental representation. More precisely, since the Fayet-Iliopoulos terms are scalars whose value may be freely chosen, the quantities entering the curve should be associated with \( v \cdot \lambda \) where \( \lambda \) is the particular weight and \( v \) is a vector of the same dimension as the rank of the group. This ensures that we can choose the Fayet-Iliopoulos parameters to be zero, corresponding to a zero value for \( v \) and when we turn on the Fayet-Iliopoulos parameters it corresponds to giving \( v \) a non-zero value such
Figure 6: The $E_6$ invariants.

that the quantities above agree. This observation will be used later to write the result for the $E_6$ curve in a nice form.

We now turn to the $E$-series. The labeling of the nodes for $E_6$ is given in Figure 6a), and the invariant polynomials $U, V$ and $W$ are defined in Figure 6b). The relation between $U$ and its orientation reversed image $\bar{U}$ is:

$$U + \bar{U} = -W^2 + A_W W + A_V V + A_0 ,$$

(3.18)

where

$$A_V \equiv \sum_{i=1}^{3} b_i(b_i - b_{i+3}) - \frac{1}{4}(\sum_{i=1}^{3} b_i + b_7)^2 ,$$

$$A_W \equiv \frac{1}{4}(\sum_{i=1}^{3} b_i + b_7)(b_4 + b_5 - b_1 - b_2 + b_7)(b_1 + b_2 - b_3 + b_7) - b_1 b_5(b_1 - b_4) + b_2(2b_1 - b_4)(b_2 - b_5)$$

(3.19)

$$A_0 \equiv -b_2(b_1 + b_3 - b_4 - b_6 - b_7)C_0 ,$$

$$C_0 \equiv b_1(b_1 - b_4)(b_1 - b_4 - b_7)(b_1 - b_4 - b_6 - b_7) .$$

Just as in the $D_4$ case (c.f. Figure 4d) the curve follows from expressing $U^2$ as $U(-\bar{U} + ...)$. The result is

$$U^2 - U(-W^2 + A_W W + A_V V + A_0) + V[V + C_W W + C_0][V + D_W W + D_0] = 0$$

(3.20)
where
\[ C_W \equiv b_1 - b_2 - b_3 + b_5 + b_6 + b_7 , \]
\[ D_W \equiv b_1 - b_2 + b_3 - b_4 - b_6 - b_7 , \]
\[ D_0 \equiv \frac{1}{27} \left[ 2b_1^3 - \frac{22}{3} (3b_1 - b_2 + b_3 - b_7)(\frac{1}{3} b_1 + b_2 - b_3 - b_7) (\frac{1}{3} b_1 - b_2 + b_3 - 2b_6 - b_7) \right. \]
\[ + 3b_1 \left\{ (2b_1 - b_2 - 2b_4 + b_5)(b_1 - 2b_2 - b_4 + 2b_5) - 2 (b_6^2 + (b_2 - b_3)(b_2 - b_3 + b_6)) \right\} \right] \]
\[ \times (b_1 + b_3 - b_4 - b_6 - b_7) . \]  

Performing the following shifts
\[ U = X + \frac{1}{2} (-W^2 + A_W W + A_V V + A_0) , \]
\[ V = Y - \frac{1}{3} \left[ C_0 + D_0 + (C_W + D_W) W - A_V^2 / 4 \right] , \]
\[ W = \sqrt{2} Z + \frac{1}{6} \left[ 3 A_W - (A_V + \frac{2}{3} C_W D_W) (C_W + D_W) + \frac{4}{9} (C_W^3 + D_W^3) \right] , \]
the curve (3.20) is brought to the standard form
\[ X^2 + Y^3 - Z^4 + P(Z) + Q(Z) Y = 0 , \]  

where the polynomials \( P(Z) \) and \( Q(Z) \) are second order in \( Z \). The coefficients in terms of the Fayet-Iliopoulos parameters may be found by substituting (3.18), (3.19), (3.21), and (3.22) into (3.20). Direct evaluation leads to a horrible mess, but the polynomials may be expressed in terms of Casimir operators of \( E_6 \); remarkably, when we do this, we find the algebraic curve given in [24]. We now present the details of this description.

The Casimirs can be defined as the coefficients of the polynomial
\[ \det (x - \Phi) , \]
where \( \Phi \) is a matrix in the fundamental representation of \( E_6 \). We can always rotate \( \Phi \) into some element in the Cartan subalgebra \( v \cdot H \) where \( v \) is an arbitrary six dimensional vector. An explicit representation for the matrices \( H \) can be found in terms of the weights \( \lambda \) of the fundamental representation, since the weight vectors can be thought of as normalized eigenvectors of the Cartan operators with the weights as eigenvalues. The Cartan operators are thus represented as diagonal matrices with the particular weights on the diagonal, and we have
\[ \Phi = v \cdot H = \begin{pmatrix} v \cdot \lambda_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & v \cdot \lambda_{27} \end{pmatrix} . \]
The terms on the diagonal are just the expressions for the weights in terms of the Fayet-Iliopoulos parameters as discussed at the end of the derivation of the curve for the $D_k$ case. Thus we have found a way to express the Casimirs in terms of the Fayet-Iliopoulos parameters. More details as well as the final result for the curve can be found in the appendix.

It is natural to conjecture that the relation between the deformation parameters of the curve and the Fayet-Iliopoulos parameters follows the same pattern for the higher exceptional algebras [25,26]. The Fayet-Iliopoulos are to be thought of as the simple roots of the algebra and the Casimirs of the fundamental representation of the algebra (expressed in terms of the simple roots and thus in terms of the Fayet-Iliopoulos parameters) give the deformation parameters of the curve.

We note that this explicit expression stands in contrast to the implicit one of [20], which involves inverting elliptic integrals.

We now turn to the $E_7$ and $E_8$ cases.

For $E_7$ and $E_8$, we consider only the orbifold limit (no Fayet-Iliopoulos terms). In Figure 7, the quiver diagram (Figure 7a) and the basic invariant polynomials (Figure 7b) for $E_7$ are shown. We have verified that all other possible invariants either vanish or are
polynomials in these basic variables. In the $E_7$ case the orientation reversal of the highest dimension graph $X$ is just $-X$, but when we multiply them together the result does not immediately factorize into a sum over products of the basic lower dimensional variables. It therefore turns out to be convenient to define the traceless $2 \times 2$ matrices $M, N$ and $K$ as in Figure 6c. Using the bug calculus it is possible to derive the following useful relations
\[
\begin{align*}
\text{Tr} (NK) &= -Z^2 , \\
\text{Tr} (MK) &= -Y , \\
\text{Tr} (MN) &= Z , \\
\text{Tr} (N^2) &= -2Y .
\end{align*}
\] (3.26)

Using these matrices we can write the square of the highest dimensional invariant as $X^2 = Y \text{Tr} (MNKN)$. To be able to use the Schouten identity (3.2) we rewrite the trace in terms of anticommutators by anticommuting the leftmost matrix all the way to the right. We can now rewrite the trace in terms of products of traces of fewer matrices. The result, dropping terms that vanish, is
\[
\text{Tr} (MNKN) = \text{Tr} (MN) \text{Tr} (KN) - \frac{1}{2} \text{Tr} (N^2) \text{Tr} (MK) ,
\] (3.27)

which, using the relations (3.26) gives the curve
\[
X^2 + Y^3 + YZ^3 = 0 .
\] (3.28)

Figure 8: The $E_8$ invariants and some useful matrices.
Finally we turn to the $E_8$ ALE space; the quotient gauge group and matter content are described by the quiver diagram in Figure 8a), and the basic invariant polynomials are defined in Figure 8b). Again, we have verified that all other possible invariants either vanish or are polynomials in these basic variables. Since there is only one $U(1)$ group in this case it is not possible to simply factorize the square of the highest dimensional invariant $X$ into a product of lower dimensional ones and we must again use the two dimensional Schouten identity (3.2). Therefore it is useful to define the traceless $2 \times 2$ matrices $A, B$ and $C$ in Figure 8c). Using the bug calculus we derive the following identities

$$\begin{align*}
\text{Tr} (ABC) &= X , \\
\text{Tr} (AB) &= 0 , \\
\text{Tr} (BC) &= Z^2 , \\
\text{Tr} (A^2) &= -2Z , \\
\text{Tr} (B^2) &= -2Y .
\end{align*}$$

(3.29)

Squaring the highest dimensional invariant $X$ and using the one dimensional Schouten identity we can write the result as $X^2 = \text{Tr} (ABCABC)$. Rewriting the trace in terms of anticommutators by using the same trick as in the $E_7$ case we get

$$X^2 = \text{Tr} (AC) \text{Tr} (AB^2C) - \text{Tr} (BC) \text{Tr} (ACAB) ,$$

(3.30)

and using the same trick once again on the traces with four matrices we find

$$\begin{align*}
\text{Tr} (AB^2C) &= \frac{1}{2} \text{Tr} (AC) \text{Tr} (B^2) , \\
\text{Tr} (ACAB) &= -\frac{1}{2} \text{Tr} (A^2) \text{Tr} (BC) .
\end{align*}$$

(3.31)

Finally, using (3.29), we arrive at the following result for the curve

$$X^2 + Y^3 + Z^5 = 0 .$$

(3.32)

4. Other examples

There is something a bit surprising about our calculations: aside from those few nodes where we used the Schouten identities, our calculations did not in any way refer to the gauge group associated with each node of the quiver. Thus if we change the Dynkin indices of those nodes where we did not use a Schouten identity, we get the same invariants and
the same algebraic curve. However, when we consider the hyperkähler quotient, this is clearly nonsensical: the delicate balance between the dimension of the gauge group and the number of hypermultiplets is achieved only for the correct Dynkin indices: e.g., for \( D_4 \), if the central node is changed from \( U(2) \) to \( U(n) \), the resulting hyperkähler quotient has zero or negative dimension. The resolution of this paradox becomes clear when we express the fields of the hypermultiplets in “spherical”-type coordinates, that is, in terms of goldstone modes that transform under the gauge group (“angles”), and the invariants (“radii”). When the dimension of the hyperkähler quotient is zero, the hypermultiplet action depends only on the goldstone modes, and the invariants that live on the algebraic curve do not enter the dynamics (one could imagine that under some circumstances these invariants correspond to dynamically generated states of the theory, and then the nontrivial hyperkähler quotient manifold would arise); if the hyperkähler quotient would give rise to a negative dimension space, then the hypermultiplet action is not only independent of the invariants, but even of some of the goldstone modes.

\[ \text{Figure 9: Some higher dimensional examples.} \]

The graphical methods that we have developed can be used to find the algebraic curves for higher dimensional ALE spaces. A few typical examples are shown in Figure 9. We have analyzed only the orbifold limits of these examples.

For Figure 9a), there are nine linearly independent invariants as defined in Figure 10. Direct application of our method gives ten polynomial equations that these invariants satisfy. However, a little calculation shows that these ten equations are generated by five equations, leaving a complex four dimensional space as expected from the hyperkähler
Figure 10: The invariants for an eight-dimensional analog of $D_4$.

\[
U_1^2 = -W_1W_2W_4, \quad U_2^2 = -W_2W_3W_5, \quad U_3^2 = -W_2W_3 \sum_{i=1}^{5} W_i, \quad U_4^2 = -W_4W_5 \sum_{i=1}^{5} W_i,
\]

\[
4 \prod_{i=2}^{5} W_i = (W_2W_5 + W_3W_4 + W_1 \sum_{i=1}^{5} W_i)^2.
\] (4.1)

This space should be an interesting nontrivial extension of $D_4$ to higher dimensions. It is straightforward to find the ten equations with the Fayet-Iliopoulos terms turned on; however, in that case, the reduction to five equations seems to be tedious.

Figure 11: The invariants for eight-dimensional Calabi ALE spaces.

For Figure 9b), there are eight linearly independent invariants as defined in Figure 11. These obey four relations, leaving a complex four dimensional space:

\[
XY = Z^k(Z + W), \quad UV = W^l(Z + W), \quad XU = P(Z + W), \quad YV = Q(Z + W). \quad (4.2)
\]

Note that in the orbifold limit, away from the subspace $Z + W = 0$, this is just the product space $A_k \times A_l$. These spaces are well understood higher dimensional analogs of the $A_k$
ALE spaces; examples were constructed as hyperkähler quotients in [15], though they had been proposed earlier as hyperkähler spaces in [24].

For Figure 9c), there are eight linearly independent invariants as defined in Figure 12. These obey four relations, leaving a complex four dimensional space:

\[ XQ = Z(ZV + U) \]
\[ YP = Z(ZW - U) \]
\[ XY = Z(Z^2 + W - V) \]
\[ PQ = ZWV \] (4.3)

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Appendix A. Details on $E_6$

The algebraic curve for the $E_6$ case including the Fayet-Illiopoulos parameters is

$$X^2 + Y^3 + \left[\frac{1}{3}P_2 Z^2 - \frac{2}{3}P_5 Z + \frac{8}{15}P_8 - \frac{11}{45}P_2 P_6 + \frac{7}{135}P_2^4 \right] Y +$$

$$\left[-Z^4 - \left(\frac{2}{3}P_6 - \frac{7}{108}P_2^3 \right) Z^2 + \left(\frac{8}{21}P_9 - \frac{1}{18}P_2^2 P_5 \right) Z \right.$$

$$\left.- \frac{32}{135}P_{12} + \frac{298}{18225}P_2^2 P_8 + \frac{101}{218700}P_2^3 P_6 - \frac{13}{405}P_6^2 + \frac{49}{1049760}P_2^6 + \frac{19}{3645}P_2 P_5^2 \right] = 0$$

(A.1)

where the $P_i$ is the Casimir of the $i$'th order. It can be found as the coefficient of $x^{27-i}$ term of the polynomial

$$\det(x - v \cdot H)$$

(A.2)

where $v \cdot H$ is given in terms of the weights $\lambda$ of the fundamental representation as $v \cdot H = \text{diag}(v \cdot \lambda_1 \ldots v \cdot \lambda_{27})$. In particular, if we define $\chi_n \equiv \text{Tr}[(v \cdot H)^n]$, we find that we can write the relevant $P_i$ as follows

$$P_2 = -\frac{1}{7} \chi_2 ,$$

$$P_5 = \frac{1}{5} \chi_5 ,$$

$$P_6 = -\frac{1}{9} \chi_6 - \frac{1}{90} \chi_2^3 ,$$

$$P_8 = -\frac{1}{8} \chi_8 + \frac{1}{12} \chi_2 \chi_6 + \frac{1}{4608} \chi_2^4 ,$$

$$P_9 = \frac{1}{9} \chi_9 - \frac{1}{14} \chi_2 \chi_7 + \frac{1}{48} \chi_2^2 \chi_5 ,$$

$$P_{12} = -\frac{1}{12} \chi_{12} + \frac{11}{1920} \chi_2^2 \chi_8 + \frac{1}{72} \chi_6^2 - \frac{1}{1440} \chi_2^3 \chi_6 + \frac{17}{2400} \chi_2 \chi_5^2 + \frac{1}{663552} \chi_2^6 ,$$

(A.3)

where, for $E_6$\footnote{After we completed our calculations, we were informed that such formulas are derived in great generality in [28]}

$$\chi_4 = \frac{1}{12} \chi_2^2 ,$$

$$\chi_7 = \frac{7}{24} \chi_2 \chi_5 ,$$

$$\chi_{10} = \frac{7}{40} \chi_5^2 + \frac{3}{8} \chi_2 \chi_8 - \frac{7}{144} \chi_2^2 \chi_6 + \frac{7}{41472} \chi_2^5 .$$

(A.4)

To express the Casimirs in terms of the Fayet-Iliopoulos parameters, we write the weights of the fundamental representation in terms of the simple roots and recall that each $b_i$ can be thought of as the scalar product between the $v$ and its corresponding simple root.\footnote{In these formulas, we have eliminated $b_7$ using the relation $\sum_{i=1}^{3} b_i + 2 \sum_{j=1}^{6} b_i + 3b_7 = 0$. It is straightforward to use this formula to eliminate one of $b_1, b_2, b_3$, to get the expressions in terms of the more standard simple roots. We have also switched the signs of $b_1, b_2, b_3$ as compared to the text to agree with the usual conventions for the simple roots, which do not agree with the signs we read off from the quiver diagrams.}
Doing this we find

\[ v \cdot \lambda_1 = \frac{1}{3} b_5 - \frac{1}{3} b_4 - \frac{2}{3} b_1 + \frac{2}{3} b_2 \quad v \cdot \lambda_2 = \frac{1}{3} b_5 - \frac{1}{3} b_4 - \frac{2}{3} b_1 - \frac{1}{3} b_2 \]

\[ v \cdot \lambda_3 = -\frac{2}{3} b_5 - \frac{1}{3} b_4 - \frac{2}{3} b_1 - \frac{1}{3} b_2 \quad v \cdot \lambda_4 = \frac{1}{3} b_4 - \frac{1}{3} b_1 + \frac{1}{3} b_3 + \frac{2}{3} b_6 \]

\[ v \cdot \lambda_5 = -\frac{1}{3} b_5 + \frac{1}{3} b_2 - \frac{1}{3} b_3 - \frac{2}{3} b_6 \quad v \cdot \lambda_6 = \frac{1}{3} b_5 + \frac{2}{3} b_4 + \frac{1}{3} b_1 + \frac{2}{3} b_2 \]

\[ v \cdot \lambda_7 = \frac{1}{3} b_5 - \frac{1}{3} b_4 + \frac{1}{3} b_1 + \frac{2}{3} b_2 \quad v \cdot \lambda_8 = -\frac{2}{3} b_4 - \frac{1}{3} b_1 + \frac{1}{3} b_3 + \frac{2}{3} b_6 \]

\[ v \cdot \lambda_9 = \frac{1}{3} b_4 - \frac{1}{3} b_1 - \frac{2}{3} b_6 + \frac{1}{3} b_3 \quad v \cdot \lambda_{10} = -\frac{2}{3} b_4 - \frac{1}{3} b_1 - \frac{2}{3} b_6 + \frac{1}{3} b_3 \]

\[ v \cdot \lambda_{11} = \frac{1}{3} b_4 - \frac{1}{3} b_1 - \frac{2}{3} b_3 - \frac{1}{3} b_6 \quad v \cdot \lambda_{12} = -\frac{2}{3} b_4 - \frac{1}{3} b_1 - \frac{2}{3} b_3 - \frac{1}{3} b_6 \]

\[ v \cdot \lambda_{13} = \frac{2}{3} b_5 + \frac{1}{3} b_2 + \frac{1}{3} b_6 + \frac{2}{3} b_3 \quad v \cdot \lambda_{14} = \frac{2}{3} b_5 + \frac{1}{3} b_2 - \frac{1}{3} b_3 + \frac{1}{3} b_6 \]

\[ v \cdot \lambda_{15} = -\frac{1}{3} b_5 + \frac{1}{3} b_2 + \frac{1}{3} b_6 + \frac{2}{3} b_3 \quad v \cdot \lambda_{16} = -\frac{1}{3} b_5 + \frac{1}{3} b_2 - \frac{1}{3} b_3 + \frac{1}{3} b_6 \]

\[ v \cdot \lambda_{17} = \frac{2}{3} b_5 + \frac{1}{3} b_2 - \frac{1}{3} b_3 - \frac{2}{3} b_6 \quad v \cdot \lambda_{18} = -\frac{1}{3} b_5 - \frac{2}{3} b_2 + \frac{2}{3} b_3 - \frac{1}{3} b_6 \]

\[ v \cdot \lambda_{19} = -\frac{1}{3} b_5 - \frac{2}{3} b_2 - \frac{1}{3} b_3 + \frac{1}{3} b_6 \quad v \cdot \lambda_{20} = -\frac{1}{3} b_5 - \frac{2}{3} b_2 - \frac{2}{3} b_6 - \frac{1}{3} b_3 \]

\[ v \cdot \lambda_{21} = \frac{1}{3} b_5 + \frac{2}{3} b_4 + \frac{1}{3} b_1 - \frac{1}{3} b_2 \quad v \cdot \lambda_{22} = \frac{1}{3} b_5 - \frac{1}{3} b_4 + \frac{1}{3} b_1 - \frac{1}{3} b_2 \]

\[ v \cdot \lambda_{23} = -\frac{2}{3} b_5 + \frac{2}{3} b_4 + \frac{1}{3} b_1 - \frac{1}{3} b_2 \quad v \cdot \lambda_{24} = -\frac{2}{3} b_5 - \frac{1}{3} b_4 + \frac{1}{3} b_1 - \frac{1}{3} b_2 \]

\[ v \cdot \lambda_{25} = \frac{1}{3} b_4 + \frac{2}{3} b_1 + \frac{1}{3} b_3 + \frac{2}{3} b_6 \quad v \cdot \lambda_{26} = \frac{1}{3} b_4 + \frac{2}{3} b_1 + \frac{1}{3} b_3 - \frac{1}{3} b_6 \]

\[ v \cdot \lambda_{27} = \frac{1}{3} b_4 + \frac{2}{3} b_1 - \frac{2}{3} b_3 - \frac{1}{3} b_6 \]

This gives the matrix \( v \cdot H \) in terms of the Fayet-Iliopoulos terms and thus the Casimir operators \( (A.3) \). In our normalization, the weights have length squared \( \lambda \cdot \lambda = \frac{2}{3} \), which corresponds to \( \text{Tr} (T_a T_b) = 3 \delta_{ab} \) in the fundamental representation.


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