Quasiconformal Realizations of $E_6(6)$, $E_7(7)$, $E_8(8)$ and $SO(n+3, m+3)$, $N \geq 4$ Supergravity and Spherical Vectors

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Abstract: After reviewing the underlying algebraic structures we give a unified realization of split exceptional groups $F_4(4)$, $E_6(6)$, $E_7(7)$, $E_8(8)$ and of $SO(n+3, m+3)$ as quasiconformal groups that is covariant with respect to their (Lorentz) subgroups $SL(3, \mathbb{R})$, $SL(3, \mathbb{R}) \times SL(3, \mathbb{R})$, $SL(6, \mathbb{R})$, $E_6(6)$ and $SO(n, m) \times SO(1, 1)$, respectively. We determine the spherical vectors of quasiconformal realizations of all these groups twisted by a unitary character $\nu$. We also give their quadratic Casimir operators and determine their values in terms of $\nu$ and the dimension $n_V$ of the underlying Jordan algebras. For $\nu = -(n_V + 2) + i\rho$ the quasiconformal action induces unitary representations on the space of square integrable functions in $(2n_V + 3)$ variables, that belong to the principle series. For special discrete values of $\nu$ the quasiconformal action leads to unitary representations belonging to the discrete series and their continuations. The manifolds that correspond to "quasiconformal compactifications" of the respective $(2n_V + 3)$ dimensional spaces are also given. We discuss the relevance of our results to $N = 8$ supergravity and to $N = 4$ Maxwell-Einstein supergravity theories and, in particular, to the proposal that three and four dimensional U-duality groups act as spectrum generating quasiconformal and conformal groups of the corresponding four and five dimensional supergravity theories, respectively.

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1. Introduction

Earliest studies of unitary representations of four dimensional U-duality groups of extended supergravity theories were given in \([1, 2, 3]\). These representations were constructed using oscillators that transform in the same representations of the U-duality groups as the vector field strengths plus their magnetic duals. These works were motivated by the idea that in a quantum theory global symmetries must be realized unitarily on the spectrum and the composite scenarios that attempted to connect maximal \(N = 8\) supergravity with observation...
In a composite scenario proposed in [4] it was conjectured that $SU(8)$ local symmetry of $N = 8$ supergravity becomes dynamical and acts as a family unifying grand unified theory (GUT) which contains $SU(5)$ GUT as well as a family group $SU(3)$. A similar scenario leads to $E_6$ GUT with a family group $U(1)$ in the exceptional supergravity theory [8] whose U-duality group is $E_{7(-25)}$ in $d = 4$. However with the discovery of possible counter terms at higher loops it was argued that divergences would eventually spoil the finiteness properties of $N = 8$ supergravity. After the work of Green and Schwarz on anomaly cancellation in superstring theory [8] attempts at composite scenarios in supergravity were abandoned. However, recent discovery of unexpected cancellations of divergences in supergravity theories [9, 10, 11, 12, 13, 14, 15, 16, 17] has brought back the question of finiteness of $N = 8$ supergravity as well as of exceptional supergravity.

Over the last decade or so, there has been a great deal more work done on unitary representations of U-duality groups of extended supergravity theories. The renewed interest in unitary realizations of U-duality groups was due partly to the proposals that certain extensions of U-duality groups may act as spectrum generating symmetry groups of supergravity theories. Based on geometric considerations involving orbits of extremal black hole solutions in $N = 8$ supergravity and $N = 2$ Maxwell-Einstein supergravity theories with symmetric scalar manifolds, it was suggested that four dimensional U-duality groups act as spectrum generating conformal symmetry groups of the corresponding five dimensional supergravity theories [18, 19, 20, 21, 22]. This proposal was then extended to the proposal that three dimensional U-duality groups act as spectrum generating quasiconformal groups of the corresponding four dimensional supergravity theories [19, 20, 21, 22]. Quasiconformal realization of U-duality group $E_{8(8)}$ of three dimensional maximal supergravity given in [19] is the first known geometric realization of $E_{8(8)}$ and its quantization leads to the minimal unitary representation of $E_{8(8)}$ [23]. Remarkably, quasiconformal realizations exist for different real forms of all noncompact groups and their quantizations yield directly the minimal unitary representations of the respective groups [23, 24, 25, 26]. Furthermore, the quasiconformal method gives a unified approach to the minimal unitary representations of all noncompact groups and extends also to supergroups [26]. For symplectic groups $Sp(2m, \mathbb{R})$ these minimal unitary representations are simply the singleton representations.

Many results have been obtained over recent years that support the proposals that four and three dimensional U-duality groups act as spectrum generating conformal and quasiconformal groups of five and four dimensional supergravity theories with symmetric scalar manifolds, respectively. The work relating black hole solutions in four and five dimensions (4d/5d lift) [27, 28, 29, 30] is consistent with the proposal that four dimensional U-duality groups act as spectrum generating conformal symmetry groups of five dimensional supergravity theories from which they descend. Furthermore, the work of [31, 32] on using solution generating techniques to relate the known black hole solutions of five dimensional ungauged supergravity theories to each other and generate new solutions using symmetry groups of the

\footnote{For further references on the subject, see [1].}
corresponding three dimensional supergravity theories and related work on gauged supergravity theories \[33\] are in accord with these proposals.

A concrete framework for implementing the proposal that three dimensional U-duality groups act as spectrum generating quasiconformal groups was formulated in \[34, 35, 36\] for spherically symmetric stationary black holes. This framework is based on the fact that the attractor equations \[37, 38\] of spherically symmetric stationary black holes of four dimensional supergravity theories are equivalent to the equations describing the geodesic motion of a fiducial particle on the moduli space \(M_3^*\) of three dimensional supergravity theories obtained by reduction on a time-like circle\(^2\). A related analysis on non-BPS extremal black holes in theories with symmetric target manifolds was carried out in \[34, 35\]. For \(N = 2\) MESGTs defined by Euclidean Jordan algebras of degree three the manifolds \(M_3^*\) are para-quaternionic symmetric spaces

\[
M_3^* = \frac{QConf(J)}{Conf(J) \times SU(1,1)}
\]

where \(QConf(J)\) and \(Conf(J)\) are the quasiconformal and conformal groups of the Jordan algebra \(J\), respectively. When one quantizes the fiducial particle’s motion one is led to quantum mechanical wave functions that provide the basis of a unitary representation of \(QConf(J)\). BPS black holes correspond to a special class of geodesics and the twistor space \(Z_3\) of \(M_3^*\) can be identified with the BPS phase space. Then the spherically symmetric stationary BPS black hole solutions of \(N = 2\) MESGT’s are described by holomorphic curves in \(Z_3\) \[34, 35, 36, 44\]. One finds that the action of three dimensional U-duality group \(QConf(J)\) on the natural complex coordinates of the twistor space is precisely of the quasiconformal form \[36\]. Therefore the unitary representations of \(QConf(J)\) relevant for BPS black holes of \(N = 2\) MESGT’s are those induced by holomorphic quasiconformal actions of \(QConf(J)\) on the corresponding twistor spaces \(Z_3\), which belong in general to quaternionic discrete series representations of \(QConf(J)\) \[34\].

Another result in support of the proposal that three dimensional U-duality groups act as spectrum generating groups of the corresponding four dimensional theories comes from the connection established in \[45\] between the harmonic superspace (HSS) formulation of \(N = 2, d = 4\) supersymmetric quaternionic Kähler sigma models that couple to \(N = 2\) supergravity and the minimal unitary representations of their isometry groups. One finds that for \(N = 2\) sigma models with quaternionic symmetric target spaces of the form\(^3\)

\[
\frac{QConf(J)}{Conf(J) \times SU(2)}
\]

there exists a one-to-one mapping between the quartic Killing potentials that generate the isometry group \(QConf(J)\) under Poisson brackets in the HSS formulation, and the generators

\(^2\)This was first observed in \[39\] and used in \[40, 41\] to construct static and rotating black holes in heterotic string theory.

\(^3\)\(Conf(J)\) is the compact form of \(Conf(J)\).
of the minimal unitary representation of $QConf(J)$ obtained by quantization of its quasiconformal realization. Therefore the “fundamental spectrum” of the quantum theory must fit into the minimal unitary representation of $QConf(J)$ and the full spectrum is obtained by tensoring of the minimal unitary representation.

In [36] unitary representations of two quaternionic groups of rank two, namely $SU(2,1)$ and $G_{2(2)}$, induced by their geometric quasiconformal actions were studied in great detail. They are the isometry groups of four and five dimensional simple $N = 2$ supergravity theories dimensionally reduced on tori to three dimensions, respectively. Unitary representations induced by the geometric quasiconformal action include the quaternionic discrete series representations that were studied in mathematics literature using other methods [46]. In the study of unitary representations of $SU(2,1)$ and $G_{2(2)}$, in particular of quaternionic discrete series, studied in [36] spherical vectors of maximal compact subgroups under their quasiconformal actions play an essential role. In a recent paper [47] we gave a unified quasiconformal realization of three dimensional U-duality groups $QConf(J)$ of all $N = 2$ MESGTs with symmetric scalar manifolds defined by Euclidean Jordan algebras of degree three in a basis covariant with respect to their 5 dimensional U-duality groups. These three dimensional U-duality groups are $F_4(4), E_6(2), E_7(-5), E_8(-24)$ and $SO(n_V + 2,4)$ and their five dimensional U-duality groups are $SL(3,\mathbb{R}), SL(3,\mathbb{C}), SU^*(6), E_6(-26)$ and $SO(1,1) \times SO(n_V - 1,1)$, respectively\(^4\). We gave their quadratic Casimir operators and determined their values and most importantly presented the spherical vectors of all these quasiconformal groups in a unified manner, which are essential for the construction of the quaternionic discrete series representations.

In this paper we extend the results of [47] to the split exceptional groups $E_6(6), E_7(7), E_8(8)$ and $SO(n+3, m+3)$, which are the quasiconformal groups of split non-Euclidean Jordan algebras of degree three\(^5\). More specifically, in section 2 we review the necessary background regarding Euclidean and non-Euclidean Jordan algebras of degree three and their rotation (automorphism) and Lorentz (reduced structure) groups. The U-duality symmetries of maximal supergravity in five, four and three dimensions are simply the Lorentz, conformal and quasiconformal groups of the split exceptional Jordan algebra $J_{OS}^{3S}$. The corresponding symmetry groups of $N = 4$ (sixteen supercharges) Maxwell-Einstein-Supergravity theories are determined by the non-simple Jordan algebras $\mathbb{R} \oplus \Gamma_{(5,n)}$. In section 3 we review the conformal symmetry groups of the relevant Jordan algebras. In Section 4 we present the unified quasiconformal realizations of $E_6(6), E_7(7), E_8(8)$ and $SO(n + 3, m + 3)$ twisted by a unitary character $\nu$ and their commutation relations as well as their quadratic Casimir operators. We determine the values of the Casimir operators as a function of $\nu$ and the dimension $n_V$ of the underlying Jordan algebra $J$. From this we determine the values of $\nu$ for which the quasiconformal action induces unitary representations on the space of square integrable functions in $(2n_V + 3)$ variables, that belong to the principle series. In section 5 we present

\(^4\)Of course, the rank two quaternionic quasiconformal groups can be obtained as a trivial limit of the general unified formulation.

\(^5\)Actually, maximally split orthogonal groups correspond to the case $n = m$. For $n = 1$ one gets the quasiconformal group of a Euclidean Jordan algebra.
the spherical vectors of these quasiconformal groups in a unified manner and discuss each
group separately. We also present the compact spaces corresponding to the “quasiconformal
compactification” of the $(2n_V + 3)$ dimensional spaces on which the quasiconformal groups
$QConf(J)$ act for all Jordan algebras of degree three, Euclidean as well as split. In section
6 we point out the connection between real and split exceptional Jordan algebras of degree
three and the quaternionic Jordan algebras of degree four and discuss the similarities and
differences between the exceptional $\mathcal{N} = 2$ supergravity and maximal $\mathcal{N} = 8$ supergravity as
they relate to quaternionic Jordan algebras of rank four.

2. Euclidean (compact) and non-Euclidean (noncompact) Jordan algebras
of Degree Three

Referring to the monograph [48] for details and references on the subject we shall give a brief
review of Jordan algebras in this section, focussing mainly on Jordan algebras of degree three.
A Jordan algebra over a field $\mathbb{F}$, which we take to generally to be the real numbers $\mathbb{R}$, is
an algebra, $J$, with a symmetric product $\circ$

$$X \circ Y = Y \circ X \in J, \quad \forall \ X, Y \in J,$$

(2.0.1)
such that the Jordan identity holds:

$$X \circ (Y \circ X^2) = (X \circ Y) \circ X^2,$$

(2.0.2)
where $X^2 \equiv (X \circ X)$. Hence a Jordan algebra is commutative and in general not associative
algebra. They were introduced by Pascual Jordan in his attempt to generalize the formalism
of quantum mechanics and finite dimensional simple Jordan algebras were classified by him,
von Neumann and Wigner [49].

A Jordan algebra $J$ is said to be Euclidean if for any two elements $X$ and $Y$ of $J$ the condition

$$X \circ X + Y \circ Y = 0$$

implies that both $X$ and $Y$ must vanish. Since the automorphism groups of Euclidean Jordan
algebras are compact they are also referred to as compact. Otherwise the Jordan algebra
is referred to as noncompact or non-Euclidean. One can in general define a norm form,
$N: J \to \mathbb{R}$ over $J$ that satisfies the composition property [31]

$$N(\{X, Y, Z\}) = N^2(X)N(Y)$$

(2.0.3)
where $\{X, Y, Z\}$ is the Jordan triple product defined as

$$\{X, Y, Z\} = X \circ (Y \circ Z) + Z \circ (Y \circ X) - (X \circ Z) \circ Y$$

(2.0.4)
The degree, $p$, of the norm form as well as of $J$ is defined by the homogeneity condition
$N(\lambda X) = \lambda^p N(X)$, where $\lambda \in \mathbb{R}$.
2.1 Euclidean Jordan Algebras of degree three and $5D$, $N = 2$ MESGT’s

As was shown in [51], there exists a one-to-one correspondence between Euclidean Jordan algebras of degree three and the $5D$, $N = 2$ MESGT’s whose scalar manifolds are symmetric spaces such that $G$ is a symmetry of their Lagrangian. In these theories the symmetric C-tensor that describes the $F \wedge F \wedge A$ type coupling

$$C_{IJK} \epsilon_{\mu \nu \lambda \rho} F^{I \mu \nu} F^{J \lambda \rho} A^{J \sigma}$$

of all the vector fields including the graviphoton is identified with the symmetric tensor that defines the cubic norm of the corresponding Euclidean Jordan algebra $J$ of degree three. Their scalar manifolds are of the form

$$\mathcal{M}_5(J) = \frac{\text{Str}_0(J)}{\text{Aut}(J)}$$

(2.1.5)

where $\text{Str}_0(J)$ is the Lorentz (reduced structure) group of $J$ and $\text{Aut}(J)$ is its rotation (automorphism) group. For Euclidean Jordan algebras the rotation (automorphism) groups are compact.

There exists an infinite family of non-simple Jordan algebras of degree three which are the direct sum of a one dimensional Jordan algebra $\mathbb{R}$ and a Jordan algebra $\Gamma_{(1,n-1)}$ associated with a quadratic form of Lorentzian signature:

$$J = \mathbb{R} \oplus \Gamma_{(1,n-1)}$$

(2.1.6)

which is referred to as the generic Jordan family. A simple realization of $\Gamma_{(1,n-1)}$ is provided by $2^{[n/2]} \times 2^{[n/2]}$ Dirac gamma matrices $\gamma^i$ ($i, j, \ldots = 1, \ldots, (n-1)$) of an $(n-1)$ dimensional Euclidean space together with the identity matrix $\gamma^0 = 1$ and the Jordan product $\circ$ being one half the anticommutator:

$$\gamma^i \circ \gamma^j = \frac{1}{2} \{\gamma^i, \gamma^j\} = \delta^{ij} \gamma^0$$

$$\gamma^0 \circ \gamma^0 = \frac{1}{2} \{\gamma^0, \gamma^0\} = \gamma^0$$

$$\gamma^i \circ \gamma^0 = \frac{1}{2} \{\gamma^i, \gamma^0\} = \gamma^i .$$

(2.1.7)

The quadratic norm of a general element $X = X_0 \gamma^0 + X_i \gamma^i$ of $\Gamma_{(1,n-1)}$ is defined as

$$Q(X) = \frac{1}{2^{[n/2]}} Tr X \bar{X} = X_0 X_0 - X_i X_i ,$$

where

$$\bar{X} \equiv X_0 \gamma^0 - X_i \gamma^i .$$

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6We should note that a given $N = 2$ MESGT in five dimensions is uniquely determined by the C-tensor.
The norm of a general element $\xi \oplus X$ of the non-simple Jordan algebra $J = \mathbb{R} \oplus \Gamma_{(1,n-1)}$ is simply given by

$$N(\xi \oplus X) = \xi Q(X)$$  \hspace{1cm} (2.1.8)

where $\xi \in \mathbb{R}$.

The scalar manifolds of corresponding 5D, $N = 2$ MESGT's are

$$\mathcal{M} = \frac{SO(n-1,1)}{SO(n-1)} \times SO(1,1)$$

In addition to the generic infinite family there exist four simple Euclidean Jordan algebras of degree three. They are generated by Hermitian $(3 \times 3)$-matrices over the four division algebras $\mathbb{A} = \mathbb{R}, \mathbb{C}, \mathbb{H}, \mathbb{O}$

$$J = \begin{pmatrix} \alpha & Z & \bar{Y} \\ \bar{Z} & \beta & X \\ Y & \bar{X} & \gamma \end{pmatrix}$$

where $\alpha, \beta, \gamma \in \mathbb{R}$ and $X, Y, Z \in \mathbb{A}$ with the product being one half the anticommutator. They are denoted as $J^R_3, J^C_3, J^H_3, J^O_3$, respectively, and the corresponding $N = 2$ MESGts are called “magical supergravity theories”. They have the 5D scalar manifolds:

- $J^R_3: \mathcal{M} = SL(3,\mathbb{R})/SO(3)$
- $J^C_3: \mathcal{M} = SL(3,\mathbb{C})/SU(3)$
- $J^H_3: \mathcal{M} = SU^*(6)/USp(6)$
- $J^O_3: \mathcal{M} = E_{6(-26)}/F_4$  \hspace{1cm} (2.1.9)

The cubic norm form, $N$, of the simple Jordan algebras of degree three is given by the “determinant” of the corresponding Hermitian $(3 \times 3)$-matrices (modulo an overall scaling factor).

$$N(J) = \alpha\beta\gamma - \alpha X \bar{X} - \beta YY - \gamma ZZ + 2 Re(XYZ)$$  \hspace{1cm} (2.1.10)

where $Re(XYZ)$ denotes the real part of $XYZ$ and bar denotes conjugation in the underlying division algebra.

For a real quaternion $X \in \mathbb{H}$ we have

$$X = X_0 + X_1j_1 + X_2j_2 + X_3j_3$$
$$\bar{X} = X_0 - X_1j_1 - X_2j_2 - X_3j_3$$
$$XX = X_0^2 + X_1^2 + X_2^2 + X_3^2$$  \hspace{1cm} (2.1.11)

where the imaginary units $j_i$ satisfy

$$j_ij_j = -\delta_{ij} + \epsilon_{ijk}j_k$$  \hspace{1cm} (2.1.12)
For a real octonion $X \in \mathbb{O}$ we have
\[
X = X_0 + X_1 j_1 + X_2 j_2 + X_3 j_3 + X_4 j_4 + X_5 j_5 + X_6 j_6 + X_7 j_7
\]
\[
\bar{X} = X_0 - X_1 j_1 - X_2 j_2 - X_3 j_3 - X_4 j_4 - X_5 j_5 - X_6 j_6 - X_7 j_7
\]
\[
X \bar{X} = X_0^2 + \sum_{A=1}^{7} (X_A)^2
\]
(2.1.13)

Seven imaginary units of real octonions satisfy
\[
j_{A}j_{B} = -\delta_{AB} + \eta_{ABC} j_{C}
\]
(2.1.14)

where $\eta_{ABC}$ is completely antisymmetric and in the conventions of \[12\] take on the values
\[
\eta_{ABC} = 1 \Leftrightarrow (ABC) = (123), (471), (572), (673), (624), (435), (516)
\]
(2.1.15)

The automorphism group of the division algebra of octonions is the compact group $G_2$.

We should note that the simple Jordan algebras $J^A_3$ of degree 3 have nonsimple subalgebras generated by elements of the form
\[
J = \begin{pmatrix}
\alpha & 0 & 0 \\
0 & \beta & X \\
0 & 0 & \bar{X} \gamma
\end{pmatrix}
\]
that are isomorphic to generic Jordan algebras $(\mathbb{R} \oplus \Gamma_{(1,2)})$, $(\mathbb{R} \oplus \Gamma_{(1,3)})$, $(\mathbb{R} \oplus \Gamma_{(1,5)})$ and $(\mathbb{R} \oplus \Gamma_{(1,9)})$ for $A = \mathbb{R}, \mathbb{C}, \mathbb{H}$ and $\mathbb{O}$, respectively.

### 2.2 Non-Euclidean Jordan algebras of degree three and 5D, $N \geq 4$ Supergravity Theories

In the generic infinite family of non-simple Jordan algebras of degree three, $\mathbb{R} \oplus \Gamma$, one can take the quadratic form defining the Jordan algebra $\Gamma$ of degree two to be of arbitrary signature different from Minkowskian, which result in non-compact or non-Euclidean Jordan algebras. If the quadratic norm form has signature $(n, m)$ we shall denote the Jordan algebra as $\Gamma_{(n,m)}$. $\Gamma_{(n,m)}$ is realized by $2^{[(n+m)/2]} \times 2^{[(n+m)/2]}$ Dirac gamma matrices $\gamma^i$ $(i, j, \ldots = 1, \ldots, (n + m - 1))$ together with the identity matrix $\gamma^0 = 1$ and the Jordan product $\circ$ being one half the anticommutator:

![Figure 1: Multiplication table of imaginary units of real octonions $\mathbb{O}$. Three imaginary units on each side, height and circle correspond to the imaginary units of a quaternion subalgebra. The arrows represent the positive directions for multiplication, e.g. $j_1 j_2 = -j_2 j_1 = j_3$ and $j_6 j_2 = -j_2 j_6 = j_4$, etc.](image-url)
\[ \gamma^i \circ \gamma^j = \frac{1}{2} \{ \gamma^i, \gamma^j \} = \eta^{ij} \gamma^0 \]
\[ \gamma^0 \circ \gamma^0 = \frac{1}{2} \{ \gamma^0, \gamma^0 \} = \gamma^0 \]
\[ \gamma^i \circ \gamma^0 = \frac{1}{2} \{ \gamma^i, \gamma^0 \} = \gamma^i . \quad (2.2.16) \]

where
\[ \eta^{ij} = \delta^{ij} \quad \text{for} \ i, j, .. = 1, 2, .., (n - 1) \]
\[ \eta^{ij} = -\delta^{ij} \quad \text{for} \ i, j, .. = n, n + 1, .., (n + m - 1) \quad (2.2.17) \]

The quadratic norm of a general element \( X = X_0 \gamma^0 + X_i \gamma^i \) of \( \Gamma_{(n,m)} \) is given by
\[ Q(X) = \frac{1}{2^{(n/2)}} \text{Tr} \bar{X}X = X_0X_0 + \eta^{ij}X_iX_j , \]
where
\[ \bar{X} \equiv X_0 \gamma^0 - X_i \gamma^i . \]

The norm of a general element \( \xi \oplus X \) of non-simple Jordan algebra \( J = \mathbb{R} \oplus \Gamma_{(n,m)} \) is simply given by
\[ N(\xi \oplus X) = \xi Q(X) \quad (2.2.18) \]
where \( \xi \in \mathbb{R} \). The invariance group of the cubic norm is
\[ \text{Str}_0(\mathbb{R} \oplus \Gamma_{(n,m)}) = SO(1,1) \times SO(n,m) \quad (2.2.19) \]

If one replaces the underlying division algebra \( A \) of three of the four simple Euclidean Jordan algebras \( J_3^A \) by the corresponding split composition algebras \( A_S \) one obtains non-Euclidean simple Jordan algebras \( J_3^{A_S} \) for \( A_S = \mathbb{C}_S, \mathbb{H}_S \) and \( \mathbb{O}_S \). For split octonions \( \mathbb{O}_S \), four of the seven “imaginary units” square to +1, while the other three square to -1. If we denote the split imaginary units as \( j^s_\mu \) (\( \mu = 4, 5, 6, 7 \)) and the imaginary units of the real quaternion subalgebra as \( j_i, (i = 1, 2, 3) \) we have:
\[ j^s_\mu j^s_\nu = \delta_{\mu \nu} - \eta_{\mu \nu} j_i \]
\[ j_i j_j = -\delta_{ij} + \epsilon_{ijk} j_k \]
\[ j_i j^s_\mu = \eta_{\mu \nu} j^s_\nu \quad (2.2.20) \]

where \( \eta_{ABC} \) (\( A, B, C = 1, 2, .., 7 \)) are the structure constant of the real octonion algebra \( \mathbb{O} \) defined above. For a split octonion
\[ O_s = o_0 + o_1 j_1 + o_2 j_2 + o_3 j_3 + o_4 j^s_4 + o_5 j^s_5 + o_6 j^s_6 + o_7 j^s_7 \]
the norm is
\[ O_s \hat{O}_s = o_0^2 + o_1^2 + o_2^2 + o_3^2 - o_4^2 - o_5^2 - o_6^2 - o_7^2 \]

\[ \text{– 9 –} \]
where $\bar{O}_s = o_0 - o_1 j_1 - o_2 j_2 - o_3 j_3 - o_4 j_4^s - o_5 j_5^s - o_6 j_6^s - o_7 j_7^s$. The norm has the invariance group $SO(4,4)$. The automorphism group of split octonions is the exceptional group $G_2(2)$ with the maximal compact subgroup $SU(2) \times SU(2)$.

The automorphism group of the split exceptional Jordan algebra defined by $3 \times 3$ split octonionic Hermitian matrices of the form

\[
J^s = \begin{pmatrix}
\alpha & Z^s & \bar{Y}^s \\
\bar{Z}^s & \beta & X^s \\
Y^s & \bar{X}^s & \gamma
\end{pmatrix}
\]

(2.2.21)

is the noncompact group $F_4(4)$ with the maximal compact subgroup $USp(6) \times SU(2)$ and its reduced structure group is $E_6(6)$ with the maximal compact subgroup $USp(8)$.

The split exceptional Jordan algebra has a subalgebra generated by elements of the form

\[
J^s = \begin{pmatrix}
\alpha & 0 & 0 \\
0 & \beta & X^s \\
0 & \bar{X}^s & \gamma
\end{pmatrix}
\]

(2.2.22)

which is isomorphic to $(\mathbb{R} + \Gamma(5,5))$, whose reduced structure and automorphism groups are $SO(5,5) \times SO(1,1)$ and $SO(4,5)$, respectively.

The split quaternion algebra $H^s$ has two “imaginary units” $j^s_m$ $(m = 2, 3)$ that square to $+1$:

\[
j^s_mj^s_n = \delta_{mn} - \epsilon_{mnk}\bar{j}^s_k
\]

(2.2.23)

\[
(j_1)^2 = -1
\]

\[
j_1j^s_m = \epsilon_{1mn}j^s_n
\]

For a split quaternion

\[
Q^s = q_0 + q_1 j_1 + q_2 j_2^s + q_3 j_3^s
\]

the norm is

\[
Q^s\bar{Q}^s = q_0^2 + q_1^2 + q_2^2 - q_3^2
\]

where $\bar{Q}^s = q_0 - q_1 j_1 - q_2 j_2^s - q_3 j_3^s$ and it is invariant under $SO(2, 2)$. The automorphism group of the split Jordan algebra $J^{33_s}$ is $Sp(6, \mathbb{R})$ with the maximal compact subgroup $SU(3) \times U(1)$. Its reduced structure group is $SL(6, \mathbb{R})$.

The split complex numbers have an “imaginary unit” that squares to $+1$ and the norm has $SO(1,1)$ invariance. The automorphism group of split complex Jordan algebra $J^{C_3_s}$ is $SL(3, \mathbb{R})$ and its reduced structure group is

\[
SL(3, \mathbb{R}) \times SL(3, \mathbb{R})
\]

The invariant tensor $C_{IJK}$ defining the cubic norm of the Jordan algebra $(\mathbb{R} \oplus \Gamma_{(5,n)})$ can be identified with the C-tensor in the $F \wedge F \wedge A$ coupling

\[
C_{IJK}F^J \wedge F^J \wedge A^K = C_{IJK}\epsilon_{\mu\nu\lambda\sigma\rho}F^{I\mu\nu}F^{J\lambda\sigma}A^K\rho
\]

(2.2.24)
of \((n + 5)\) vector fields of \(N = 4\) MESGT’s that describe the coupling of \(n\) vector multiplets to \(N = 4\) supergravity in five dimensions. Scalar manifolds of these theories are symmetric spaces
\[ \mathcal{M}_5 = \frac{SO(5, n) \times SO(1, 1)}{SO(5) \times SO(n)} \]  
(2.2.25)

where the isometry group \(SO(5, n) \times SO(1, 1)\) is simply the reduced structure group of the Jordan algebra \((\mathbb{R} \oplus \Gamma_{(5,n)})\).

The bosonic field content of \(N = 6\) simple supergravity is the same as that of \(N = 2\) MESGT defined by the Euclidean Jordan algebra \(J^E_3\). Hence the scalar manifold of \(N = 6\) supergravity is
\[ \mathcal{M}_5(N = 6) = \frac{\text{Str}_0(J^E_3)}{\text{Aut}(J^E_3)} = \frac{SU^*(6)}{USp(6)} \]  
(2.2.26)

Therefore its invariant C-tensor is simply the one given by the cubic norm of \(J^E_3\), which is a Euclidean Jordan algebra.

As for \(N = 8\) supergravity in five dimensions its C-tensor is simply the one given by the cubic norm of the split exceptional Jordan algebra \(J^O_3\) defined over split octonions \(O_S\). \(E_{6(6)}\) is the invariance group of the C-tensor as well as of the full maximal supergravity in five dimensions whose scalar manifold is
\[ \mathcal{M}_5(N = 8) = \frac{E_{6(6)}}{USp(8)} \]  
(2.2.27)

The five dimensional \(N = 8\) supergravity can be truncated to \(N = 4\) MESGT describing the coupling of 5 vector multiplets to \(N = 4\) supergravity with the scalar manifold
\[ \frac{SO(1, 1) \times SO(5, 5)}{SO(5) \times SO(5)} \]  
(2.2.28)

The C-tensor of this truncated theory coincides with the symmetric tensor that defines the cubic norm of the Jordan subalgebra \((\mathbb{R} \oplus \Gamma_{(5,5)})\) of \(J^O_3\) given above.

3. Conformal Groups of Jordan Algebras and U-duality groups in \(d = 4\)

The proposal [53] to define generalized spacetimes coordinatized by elements of a Jordan algebra \(J\) identifies the automorphism \(\text{Aut}(J)\) and reduced structure groups \(\text{Str}_0(J)\) of the Jordan algebra \(J\) with the rotation and Lorentz groups of the corresponding spacetime respectively. The Lorentz group and dilatations generate the structure group \(\text{Str}(J)\) of \(J\), which extends to the generalized conformal group \(\text{Conf}(J)\) of the Jordan algebra \(J\). \(\text{Conf}(J)\) can be identified with the invariance group of the light cone defined by the norm form of the Jordan algebra \(J\) [53, 54, 55, 19]. For Euclidean Jordan algebras of dimensions \(n\) defined by a quadratic norm form with a Lorentzian signature the rotation, Lorentz and conformal groups are simply \(SO(n-1), SO(n-1,1)\) and \(SO(n,2)\), respectively.

Lie algebra \(\text{conf}(J)\) of the generalized conformal group \(\text{Conf}(J)\) has a natural 3-grading with respect to the dilatation generator \(R\). Choosing a basis \(e_I\) for the Jordan algebra and
labelling the translations and special conformal generators as \( T_I \) and \( K^I \), respectively, we have

\[
\text{conf}(J) = T_I \oplus R^I_J \oplus K^I
\]

(3.1)

where \( I, J, \ldots = 1, 2, \ldots, \text{dim}(J) = n_V \). Traceless components \( L^I_J \) of \( R^I_J \) are the Lorentz group generators and the trace part is proportional to the dilatation generator \( \mathcal{R} \):

\[
\mathcal{R} = \frac{1}{n_V} R^K_K
\]

(3.2)

\[
R^I_J = L^I_J + \delta^I_J \mathcal{R}
\]

In the chosen basis \( e_I \) for the Jordan algebra an element \( x \in J \) can be written as \( x = e_I q^I = \tilde{e}^I q_I \). Then the action of the generators of \( \text{conf}(J) \) on \( J \) can be written as differential operators acting on the “coordinates” \( q^I \). These generators can be twisted by a unitary character \( \lambda \) and take the simple form

\[
T_I = \frac{\partial}{\partial q^I}
\]

\[
R^I_J = -\Lambda^{JK}_{IL} q^L \frac{\partial}{\partial q^K} - \lambda \delta^I_J
\]

(3.3)

\[
K^I = \frac{1}{2} \Lambda^{JK}_{IL} q^J q^L \frac{\partial}{\partial q^K} + \lambda q^I
\]

(3.4)

They satisfy the commutation relations

\[
[T_I, K^J] = -R^I_J
\]

(3.5)

\[
[R^I_J, T_K] = \Lambda^{KL}_{IJ} T_L
\]

(3.6)

\[
[R^I_J, K^K] = -\Lambda^{IJ}_{KL} K^L
\]

(3.7)

where \( \Lambda^{IJ}_{KL} \) are the structure constants of the Jordan triple product

\[
\{ e_I, e^K, e_J \} = \Lambda^{KL}_{IJ} e_L
\]

(3.8)

\[
\{ \tilde{e}^K, e_I, \tilde{e}^L \} = \Lambda^{KL}_{IJ} \tilde{e}^J
\]

(3.9)

The generators of rotation (automorphism) group \( \text{Aut}(J) \) are

\[
A_{IJ} = R^I_J - R^J_I
\]

(3.10)

For Jordan algebras of degree three the structure constants can be written as

\[
\Lambda^{IJ}_{KL} := \delta^I_K \delta^J_L + \delta^I_L \delta^J_K - \frac{4}{3} C^{IJM} C_{KLM}
\]

(3.11)

Footnote 7: Note that there are, in general, two inequivalent actions of the reduced structure group: one on Jordan algebra and another one on its conjugate (or dual). The tilde refers to the conjugate basis such that \( q_I p^I \) is invariant under the action of reduced structure group \( \text{Str}_0(J) \). For details on this issue see [55].
where $C_{IJK}$ is the symmetric tensor that defines the cubic norm of $J$ and satisfies the “adjoint identity” \[^{51}\]:

$$C^{IJK}C_{J(MNP)}^{|K} = \delta^I_MC_{NPQ}$$

Since the $C$-tensor is an invariant of the Lorentz (reduced structure) group we have

$$C_{IJK} = C^{IJK}$$

The conformal groups of non-Euclidean Jordan algebras $J^3$, $J^6$, $J^7$, and $(\mathbb{R} \oplus \Gamma_{(m,n)})$ are listed in Table 1. The conformal group of $J^6$ is $E_7(7)$ which is the U-duality group of maximal supergravity in $d = 4$. Similarly, the conformal groups $SO(6, n + 1) \times SU(1, 1)$ of the Jordan algebras $(\mathbb{R} \oplus \Gamma_{(5,n)})$ are the U-duality groups of $N = 4$ MSGTs in $d = 4$.

### 4. Quasiconformal Groups associated with Non-Euclidean Jordan Algebras of Degree Three

Quasiconformal realizations of Lie groups was first formulated over Freudenthal triple systems associated with Lie groups extended by an extra singlet coordinate \[^{19}\]. Given a simple Lie algebra $\mathfrak{g}$ one can associate a Freudenthal triple system $\mathcal{F}$ with it via the Freudenthal-Kantor construction \[^{56}\] using the 5-grading of $\mathfrak{g}$

$$\mathfrak{g} = g^{-2} \oplus g^{-1} \oplus g^0 \oplus g^1 \oplus g^2$$

such that grade $\pm 2$ subspaces are one dimensional. The generators of grade $+1$ and by conjugation also of $-1$ subspaces are labelled by the elements of the underlying FTS:

$$\mathfrak{g} = \tilde{K} \oplus \tilde{U}_A \oplus S_{AB} \oplus U_B \oplus K$$

where $A, B \in \mathcal{F}$. Here we shall focus on quasiconformal realizations of groups associated with FTS’s defined by non-Euclidean Jordan algebras $J$ of degree three in a basis covariant with respect to their Lorentz (reduced structure) groups. The elements of a FTS $\mathcal{F}(J)$ defined over $J$ can be represented as formal $2 \times 2$ “matrices”

$$X = \begin{pmatrix} \alpha & x \\ y & \beta \end{pmatrix}$$

### Table 1

Above we give the automorphism ($Aut(J)$), reduced structure ($Str_0(J)$), conformal ($Conf(J)$) and quasiconformal groups ($QConf(J)$) associated with non-Euclidean Jordan algebras of degree three.

| $J$               | $Aut(J)$       | $Str_0(J)$       | $Conf(J)$       | $QConf(J)$       |
|-------------------|----------------|------------------|-----------------|------------------|
| $J^3_3$           | $SL(3, \mathbb{R})$ | $SL(3, \mathbb{R}) \times SL(3, \mathbb{R})$ | $SL(6, \mathbb{R})$ | $E_6(6)$         |
| $J^6_3$           | $Sp(6, \mathbb{R})$ | $SL(6, \mathbb{R})$ | $SO(6, 6)$      | $E_7(7)$         |
| $J^7_3$           | $F_4(4)$       | $E_6(6)$         | $E_7(7)$        | $E_8(8)$         |
| $\mathbb{R} \oplus \Gamma_{(n,m)}$ | $SO(n - 1, m)$ | $SO(1, 1) \times SO(n, m)$ | $SO(n + 1, m + 1) \times SU(1, 1)$ | $SO(n + 3, 3 + m)$ |
where $\alpha, \beta \in \mathbb{R}$ and $x, y \in J$. We shall write $X$ simply as $X \equiv (\alpha, \beta, x, y)$ for convenience. Every FTS admits a skew-symmetric bilinear form. Given two elements $X = (\alpha, \beta, x, y)$ and $Y = (\gamma, \delta, w, z)$ of $\mathcal{F}(J)$ their skew symmetric bilinear form is
\[
\langle X, Y \rangle \equiv \alpha \delta - \beta \gamma + (x, z) - (y, w) \tag{4.0.4}
\]
where $(x, z)$ is the symmetric bilinear form over $J$ given by the trace $\text{Tr}$:
\[
(x, z) \equiv \text{Tr} (x \circ z) \tag{4.0.5}
\]
In the normalization and conventions of [19] the quartic norm $Q_4(X)$ of $X \in \mathcal{F}(J)$ is given by
\[
Q_4(X) \equiv \frac{1}{48} \langle (X, X, X), X \rangle \tag{4.0.6}
\]
where $(X, Y, Z)$ denotes the Freudenthal triple product. The automorphism group of the FTS $\mathcal{F}(J)$ is isomorphic to the conformal group of the Jordan algebra $J$:
\[
\text{Aut}(\mathcal{F}(J)) \cong \text{Conf}(J) \tag{4.0.7}
\]
We note that under the action of $\text{Aut}(\mathcal{F}(J))$ the elements $X = (\alpha, \beta, x, y) \in \mathcal{F}(J)$ transform linearly, which is not to be confused with the nonlinear action of the conformal group $\text{Conf}(J)$ on $J$. Under the Lorentz subgroup $\text{Str}_0(J)$ of $\text{Aut}(\mathcal{F}(J))$ the Jordan components $x$ and $y$ of $X$ transform in conjugate (dual) representations.

For 5d supergravity theories whose C-tensors are given by the norm forms of Jordan algebras $J$ of degree three one-to-one correspondence between the vector fields and the elements of $J$ gets extended to a one-to-one correspondence between the vector field strengths and their magnetic duals and elements of the Freudenthal triple system $\mathcal{F}(J)$:
\[
(A^I_\mu \leftrightarrow J) \Rightarrow \left( \begin{array}{c} F^0 \\ F^I \\ \tilde{F}^I \\ \tilde{F}^0 \end{array} \right) \rightarrow \mathcal{F}(J) \]
where $F^0$ denotes the field strength of the vector field that comes from the 5d graviton. Field strengths $F^I$ and their magnetic duals $\tilde{F}^I$ transform in conjugate representations under the Lorentz group $\text{Str}_0(J)$. Since the automorphism group of a Freudenthal triple system $\mathcal{F}(J)$ defined over a Jordan algebra $J$ of degree three is isomorphic to the four dimensional U-duality group $\text{Aut}(\mathcal{F}(J)) = \text{Conf}(J)$ of corresponding supergravity theories the original formulation of [19] is covariant with respect to $\text{Conf}(J)$.

Consider now the vector space $T$ of a FTS extended by an extra coordinate. We shall denote vectors in this space as $X = (X, x) \in T$ where $X$ belongs to the FTS and $x$ is the extra coordinate. The action of Lie algebra of the quasiconformal group, associated with a
FTS $\mathcal{F}$, on the vector space $\mathcal{T}$ is given by [19, 23]:

\[
\begin{align*}
K (X) &= 0 \quad U_A (X) = A \quad S_{AB} (X) = (A, B, X) \\
K (x) &= 2 \quad U_A (x) = \langle A, X \rangle \quad S_{AB} (x) = 2 \langle A, B \rangle x \\
\hat{U}_A (X) &= \frac{1}{2} (X, A, X) - Ax \\
\hat{U}_A (x) &= -\frac{1}{6} (\langle X, X, X \rangle, A) + \langle X, A \rangle x \\
\hat{K} (X) &= -\frac{1}{6} (X, X, X) + Xx \\
\hat{K} (x) &= \frac{1}{6} (\langle X, X, X \rangle, X) + 2 x^2
\end{align*}
\] (4.0.8)

where $A, B \in \mathcal{F}$.

The quartic norm over the space $\mathcal{T}$ is defined as

\[
\mathcal{N}_4 (\mathcal{X}) := Q_4 (X) - x^2
\] (4.0.9)

where $Q_4 (X)$ is the quartic invariant of $X \in \mathcal{F}$. Quartic “symplectic distance” $d (\mathcal{X}, \mathcal{Y})$ between any two points $\mathcal{X} = (X, x)$ and $\mathcal{Y} = (Y, y)$ in $\mathcal{T}$ is defined as the quartic norm of “symplectic difference”

\[
\delta (\mathcal{X}, \mathcal{Y}) := (X - Y, x - y + \langle X, Y \rangle)
\] (4.0.10)

of two vectors in $\mathcal{T}$

\[
d (\mathcal{X}, \mathcal{Y}) := \mathcal{N}_4 (\delta (\mathcal{X}, \mathcal{Y})) = Q_4 (X - Y) - (x - y + \langle X, Y \rangle)^2
\] (4.0.11)

The quasiconformal group action defined above leaves invariant light-like separations [19]

\[
d (\mathcal{X}, \mathcal{Y}) = 0
\] (4.0.12)

In other words the quasiconformal group is the invariance group of the light-cone with respect to the quartic distance function [4.0.11]. We shall refer to the submanifold with base point $\mathcal{X}$ in the space $\mathcal{T}$ defined by the condition [4.0.12] as the “quartic light-cone”\(^8\). Quasiconformal realization of a simple Lie algebra $\mathfrak{g}$ over a FTS $\mathcal{F}$ extended by an extra singlet coordinate carries over to the complexification of $\mathfrak{g}$. Therefore by taking different real sections one can obtain quasiconformal realizations of different real forms of a the corresponding group $G$.

The quartic light-cone [4.0.11] is manifestly invariant under the Heisenberg symmetry group corresponding to “symplectic translations” generated by $U_A$ and $K$ in [4.0.8]. “Symplectic special conformal generators” $\hat{U}_A$ and $\hat{K}$ also form an Heisenberg subalgebra and their action on the quartic light-cone $d (\mathcal{X}, \mathcal{Y})$ results in overall multiplicative factors [19, 36]

\[
d (\mathcal{X}, \mathcal{Y}) \implies f (\mathcal{X}, \mathcal{Y}) d (\mathcal{X}, \mathcal{Y})
\] (4.0.13)

\(^8\)By an abuse of terminology we shall sometimes refer to the distance function [4.0.11] also as the quartic light-cone.
Above we give the $7 \times 5$ grading of the quasiconformal Lie algebra $QConf(J)$ associated with the Freudenthal triple system $F(J)$ defined over a Jordan algebra $J$ of degree 3. The vertical 5-grading is determined by $D = -\Delta$ that commutes with the Lorentz group generators $L^I_I$ and with $R$. Horizontal 7-grading is determined by $R$. The generators $\tilde{R}^I, R^I$ and $R_I$ generate the automorphism group $Aut(F(J))$ under which the generators $(U_0, U_I, V^I, V^0)$ as well as $(\tilde{U}_0, \tilde{U}_I, \tilde{V}^I, \tilde{V}^0)$ transform linearly in a symplectic representation.

which proves that light-like separations are left invariant under the full quasiconformal group action.

For supergravity theories whose 5 and 4 dimensional U-duality symmetry groups are the Lorentz and Conformal groups of a Jordan algebra $J$ of degree three the U-duality groups of corresponding 3d supergravity theories are isomorphic to the quasiconformal groups $QConf(J)$ of the Jordan algebras $J$.

### 4.1 Quasiconformal Lie Algebras of Non-Euclidean Jordan algebras of Degree Three Twisted by a Unitary Character

We shall denote the basis vectors of $F(J)$ as follows

$$\begin{pmatrix} \alpha & x \\ y & \beta \end{pmatrix} = \alpha \epsilon_0 + \beta \tilde{\epsilon}^0 + x^I \epsilon_I + y_I \tilde{\epsilon}^I$$

where $I = 1, \ldots, n_V = \text{dim}(J)$ and $x$ and $y$ transform in conjugate representations of the Lorentz group $Str_0(J)$.

The quasiconformal Lie algebra associated with a Jordan algebra $J$ of degree three which we denote interchangeably as $QConf(F(J))$ or as $QConf(J)$ can be given a 7 by 5 graded decomposition that is covariant with respect to the reduced structure group $Str_0(J)$ as shown in Table 2. With applications to supergravity theories in mind we shall label the elements $X, Y, \ldots$ of FTS $F(J)$ in terms of coordinates $(q_0, q_I)$ and momenta $(p^0, p^I)$ as follows

$$X = q_0 \tilde{\epsilon}^0 + q_I \tilde{\epsilon}^I + p^I \epsilon_I + p^0 \epsilon_0$$

---

$^9 p^I q_I = (e_I p^I, q_I \tilde{e}^I)$ and $(p^I, q^I)_I = (p^I \tilde{e}^I, q^I \epsilon_I)$. 

---
We shall normalize the basis elements and cubic norm (C-tensor) such that the quartic invariant is given by
\[
I_4(X) = (p^0 q_0 - p^I q_I)^2 - \frac{4}{3} C_{IJK} p^J p^K C^{ILM} q_L q_M
\]
\[
+ \frac{4}{3\sqrt{3}} p^0 C^{IJK} q_I q_J q_K + \frac{4}{3\sqrt{3}} q_0 C_{IJK} p^I p^K
\]
\[
= (p^0 q_0 - p^I q_I)^2 - \frac{4}{3} (p^*_I) (q^*_I)
\]
\[
+ \frac{4}{3\sqrt{3}} p^0 N(q) + \frac{4}{3\sqrt{3}} q_0 N(p)
\]

where
\[
N(q) \equiv C^{IJK} q_I q_J q_K
\]
\[
N(p) \equiv C_{IJK} p^I p^J p^K
\]

The basis vectors \( e_I \) (\( \tilde{e}^I \)) of the Jordan algebra \( J \) (and its conjugate \( \tilde{J} \)) are normalized such that
\[
(\tilde{e}^I, \tilde{e}^J) = \text{Tr} \tilde{e}^I \circ \tilde{e}^J = \eta^{IJ}
\]
\[
(e_I, e_J) = \text{Tr} e_I \circ e_J = \eta_{IJ}
\]
\[
(e_I, \tilde{e}^J) = T \text{re}_I \circ \tilde{e}^J = \delta^I_J
\]

where \( \eta_{IJ} \) is diagonal and equal to \( \delta_{IJ} \) for Euclidean (compact) elements and equal to \(-\delta_{IJ}\) for non Euclidean (noncompact) elements and will be explicitly given below. Furthermore we will label the basis elements of the Jordan algebra \( J \) such that \( e_1, e_2 \) and \( e_3 \) are the three irreducible idempotents of \( J \) and the identity element \( I \) is simply
\[
I = e_1 + e_2 + e_3
\]

The action of the generators of quasiconformal group \( QConf(J) \) on the space \( T = \mathcal{F}(J) \oplus \mathbb{R} \) with coordinates \( q_0, q_I, p^0, p^I \) of \( \mathcal{F}(J) \) plus an extra singlet coordinate \( x \in \mathbb{R} \),
twisted by a unitary character \( \nu \), is given by the following differential operators:

\[
K = \partial_x \\
U_0 = \partial_{p^0} + q_0 \partial_x \\
U_I = -\partial_{p^I} + q_I \partial_x \\
V^0 = \partial_{q_0} - p^0 \partial_x \\
V^I = \partial_{q_I} + p^I \partial_x \\
R_I = -\sqrt{2} C_{1JK} p^K \partial_{q_K} - \frac{\sqrt{3}}{2} (p^0 \partial_{p^I} + q_I \partial_{q_0}) \\
\tilde{R}_I = \sqrt{2} C_{1JK} q_J \partial_{p^K} + \frac{\sqrt{3}}{2} (q_0 \partial_{q_I} + p^I \partial_{p^0}) \\
R_I^J = \frac{3}{2} \delta_I^J (p^0 \partial_{p^0} - q_0 \partial_{q_0}) + \\
\frac{3}{2} \left( \delta_I^N \delta_K^J - \frac{4}{3} C_{1KL} C^{JNL} \right) (q_N \partial_{q_K} - p^K \partial_{p^N}) \\
R = \frac{1}{n \nu} \tilde{R}_I = \frac{3}{2} (p^0 \partial_{p^0} - q_0 \partial_{q_0}) + \frac{1}{2} (p^I \partial_{p^I} - q_I \partial_{q_I}) \\
\Delta = -\mathcal{D} = -(p^0 \partial_{p^0} + p^I \partial_{p^I} + q_0 \partial_{q_0} + q_I \partial_{q_I} - \nu) - 2x \partial_x \\
\check{K} = x (p^0 \partial_{p^0} + p^I \partial_{p^I} + q_0 \partial_{q_0} + q_I \partial_{q_I} - \nu) + (x^2 + I_4) \partial_x \\
+ \frac{1}{2} \left( \frac{\partial I_4}{\partial q^0} \partial_{q_0} - \frac{\partial I_4}{\partial q^0} \partial_{p^0} + \frac{\partial I_4}{\partial q_I} \partial_{p^I} - \frac{\partial I_4}{\partial p^I} \partial_{q_I} \right)
\]

The vertical five grading is determined by the adjoint action of \( \mathcal{D} \)

\[
\begin{bmatrix}
\mathcal{D}, \begin{pmatrix}
U_0 \\
U_I \\
V^I \\
V^0
\end{pmatrix}
\end{bmatrix} = \begin{pmatrix}
U_0 \\
U_I \\
V^I \\
V^0
\end{pmatrix}
\]

The vertical grade \(-1\) generators are obtained from the grade \(+1\) generators by commutation with the grade \(-2\) generator \( \check{K} \)

\[
\check{U}_0 = \left[ U_0, \check{K} \right] \\
\check{V}^0 = \left[ V^0, \check{K} \right] \\
\check{U}_I = \left[ U_I, \check{K} \right] \\
\check{V}^I = \left[ V^I, \check{K} \right]
\]
and satisfy

\[
[D, \begin{pmatrix} \tilde{U}_0 \\ \tilde{U}_I \\ \tilde{V}^I \\ \tilde{V}^0 \end{pmatrix}] = - \begin{pmatrix} \tilde{U}_0 \\ \tilde{U}_I \\ \tilde{V}^I \\ \tilde{V}^0 \end{pmatrix}
\]

(4.1.24)

The remaining non-vanishing commutation relations of Lie algebra of \(QCon_f(J)\) are as follows:

\[
\begin{align*}
[K, \tilde{K}] &= \Delta \\
[\Delta, K] &= -2K \\
[\Delta, \tilde{K}] &= 2\tilde{K} \\
[U_I, V^J] &= -2\delta^I_J K \\
[U_0, V^0] &= -2K \\
[K, \tilde{U}_0] &= U_0 \\
[K, \tilde{U}_I] &= U_I \\
[K, \tilde{V}^I] &= V^I \\
[K, \tilde{V}^0] &= V^0 \\
[\tilde{U}_I, \tilde{V}^J] &= -2\delta^I_J \tilde{K} \\
[\tilde{U}_0, \tilde{V}^0] &= -2\tilde{K} \\
[U_0, \tilde{V}^0] &= -2\text{R} + D \\
[V^0, \tilde{U}_0] &= -2\text{R} - D
\end{align*}
\]

(4.1.25 - 4.1.37)
\[
[R^I_J, R_K] = \frac{3}{2} \Lambda^{JL}_{IK} R_L \tag{4.1.38}
\]
\[
[R^I_J, \tilde{R}^L] = -\frac{3}{2} \Lambda^{JK}_{IL} \tilde{R}^L \tag{4.1.39}
\]
\[
[R^I_J, U_K] = \frac{3}{2} \Lambda^{JK}_{IL} U_L - \frac{3}{2} \delta^I_J U_K \tag{4.1.40}
\]
\[
[R^I_J, V^K] = -\frac{3}{2} \Lambda^{JK}_{IL} V^L + \frac{3}{2} \delta^I_J V^K \tag{4.1.41}
\]
\[
[R^I_J, \tilde{U}_K] = \frac{3}{2} \Lambda^{JK}_{IL} \tilde{U}_L - \frac{3}{2} \delta^I_J \tilde{U}_K \tag{4.1.42}
\]
\[
[R^I_J, \tilde{V}^K] = -\frac{3}{2} \Lambda^{JK}_{IL} \tilde{V}^L + \frac{3}{2} \delta^I_J \tilde{V}^K \tag{4.1.43}
\]
\[
[R^I_J, \tilde{R}^I] = -R^I_J \tag{4.1.44}
\]
\[
[U_0, \tilde{V}^I] = 2 \sqrt{\frac{2}{3}} \tilde{R}^I \tag{4.1.45}
\]
\[
[\tilde{U}_0, V^I] = -2 \sqrt{\frac{2}{3}} \tilde{R}^I \tag{4.1.46}
\]
\[
[V^0, \tilde{U}_I] = -2 \sqrt{\frac{2}{3}} R_I \tag{4.1.47}
\]
\[
[\tilde{V}^0, U_I] = -2 \sqrt{\frac{2}{3}} R_I \tag{4.1.48}
\]
\[
[U^I, \tilde{V}^J] = \frac{4}{3} R^I_J - \delta^I_J (\Delta + 2 \mathcal{R}) \tag{4.1.49}
\]
\[
[\tilde{U}^I, V^J] = -\frac{4}{3} R^I_J - \delta^I_J (\Delta - 2 \mathcal{R}) \tag{4.1.50}
\]
\[
[U^I, \tilde{U}_J] = -\frac{4}{3} \sqrt{2} C_{IJL} \tilde{R}^L \tag{4.1.51}
\]
\[
[V^I, \tilde{V}^J] = -\frac{4}{3} \sqrt{2} C^{IJL} R^L \tag{4.1.52}
\]
\[
[V^I, R_J] = -\sqrt{\frac{3}{2}} \delta^I_J V^0 \tag{4.1.53}
\]
\[
[\tilde{V}^I, R_J] = -\sqrt{\frac{3}{2}} \delta^I_J \tilde{V}^0 \tag{4.1.54}
\]
\[
[\tilde{U}^I, \tilde{R}^J] = -\sqrt{\frac{3}{2}} \delta^I_J \tilde{U}_0 \tag{4.1.55}
\]
\[
[U^I, \tilde{R}^J] = -\sqrt{\frac{3}{2}} \delta^I_J U_0 \tag{4.1.56}
\]
\[
[U^I, \tilde{R}^J] = -\sqrt{\frac{3}{2}} \delta^I_J U_0 \tag{4.1.57}
\]

where
\[
\Lambda^{IJ}_{KL} := \delta^I_K \delta^J_L + \delta^I_L \delta^J_K - \frac{4}{3} C^{IJLM} C_{KL} \tag{4.1.58}
\]

There is a distinguished $SL(3, \mathbb{R})$ subgroup of $QConf(J)$ whose centralizer is the Lorentz group $Str_0(J)$ generated by $L^I_J$, whose generators are $K$, $\tilde{K}$, $U_0$, $\tilde{U}_0$, $V^0$, $\tilde{V}^0$, $\mathcal{R}$ and $\mathcal{D}$. Its
maximal compact subgroup $SO(3) \subset SL(3, \mathbb{R})$ is generated by

$$
T_1 := \frac{1}{\sqrt{2}} \left( U_0 - \tilde{V}^0 \right)
$$

$$
T_2 := \frac{1}{\sqrt{2}} \left( V^0 + \tilde{U}_0 \right)
$$

$$
T_3 := - \left( K + \tilde{K} \right)
$$

that satisfy

$$[T_i, T_j] = \epsilon_{ijk} T_k \quad (4.1.62)$$

where $i, j, k = 1, 2, 3$. The generators of the maximal compact subgroup $K$ of $QConf(J)$ are

$$
(U_I - \eta_{IJ} \tilde{V}^J), \quad (V^I + \eta^{IJ} \tilde{U}_J), \quad (R_I + \eta_{IJ} \tilde{R}^J),
$$

$$
(R^I_J - \eta_{JK} \eta^{IJ} R^K), \quad (\tilde{U}_0 + V^0), \quad (-U_0 + \tilde{V}^0), \quad (K + \tilde{K})
$$

where $I, J, \ldots = 1, 2, \ldots, n_V$ where $n_V$ is the dimension of $J^{10}$.

4.2 Quadratic Casimir Operators of Quasiconformal Lie algebras

The generators $L^I_J$ of the reduced structure (Lorentz) group of a Jordan algebra are given by the traceless components of $R^I_J$:

$$
L^I_J = R^I_J - \frac{1}{n_V} \delta^I_J (R^K) = R^I_J - \delta^I_J R
$$

The quadratic Casimir operator of the quasiconformal group $QConf(J)$ of a simple Jordan algebra $J$ of degree three can then be written in a general form involving a single parameter $\alpha$, valid both for Euclidean and non-Euclidean $J$:

$$
C_2 = \alpha L^I_J L^I_J - \frac{4}{3} (R^2 + \tilde{R}^I R_I + R_I \tilde{R}^I) + (U_0 \tilde{V}^0 + U_I \tilde{V}^I + \tilde{V}^0 U_0 + \tilde{V}^I U_I) \quad (4.2.2)
$$

$$
- (\tilde{U}_0 V^0 + \tilde{U}_I V^I + V^0 \tilde{U}_0 + V^I \tilde{U}_I) - 2 (K \tilde{K} + \tilde{K} K) + \Delta^2
$$

\footnote{For the supergravity theories whose C-tensors are determined by a Jordan algebra, $n_V$ is the number of vector fields in 5 dimensions, hence the notation.}
where $\alpha$ takes on the following values for different quasiconformal Lie groups $QCG(J)$:

$$\alpha(F_{4(4)}) = \frac{16}{45} \quad (4.2.3)$$

$$\alpha(E_{6(6)}) = \frac{8}{27}$$

$$\alpha(E_{7(7)}) = \frac{2}{9}$$

$$\alpha(E_{8(8)}) = \frac{4}{27}$$

As for the quasiconformal groups $QConf(\mathbb{R} \oplus \Gamma_{(n,m)}) = SO(n + 3, m + 3)$ associated with the generic family of reducible Jordan algebras $J = \mathbb{R} \oplus \Gamma_{(n,m)}$ the quadratic Casimir can be written in the form:

$$C_2(SO(n + 3, m + 3)) = \frac{4}{9} R^I_I R^J_J - \frac{4}{3} (\tilde{R}^I_I R^J_J + R^I_I \tilde{R}^J_J) - \frac{(n + m - 2)}{9} (R^2_2 + R^3_3)^2$$

$$+ (U_0 V^0 + U_I V^I + \tilde{V}^0 U_0 + \tilde{V}^I U_I)$$

$$- (\tilde{U}_0 V^0 + \tilde{U}_I V^I + V^0 \tilde{U}_0 + V^I \tilde{U}_I) - 2(K\tilde{K} + \tilde{K}K) + \Delta^2 \quad (4.2.4)$$

The dimension of $J = \mathbb{R} \oplus \Gamma_{(n,m)}$ is

$$n_V = n + m + 1 \quad (4.2.5)$$

The quadratic Casimir operators for all the quasiconformal groups $QConf(J)$ reduce to a c-number whose value can be expressed universally in terms of the twisting parameter and the dimension $n_V$ of the Jordan algebra $J$ as:

$$C_2(QCG(J)) = \nu(\nu + 2n_V + 4) \quad (4.2.6)$$

As a consequence the representations induced by the quasiconformal action of $QConf(J)$ on the space of square integrable functions $L^2(p^I, q_I, x)$ of $(n_V + 1)$ coordinates $q_I$, $(n_V + 1)$ momenta and the singlet coordinate $x$ are unitary representations belonging to the principle series under the scalar product

$$\langle f | g \rangle = \int \tilde{f}(p, q, x) g(p, q, x) dp dq dx \quad (4.2.7)$$

for

$$\nu = -(n_V + 2) + i\rho \quad (4.2.8)$$

where $\rho \in \mathbb{R}$. For special discrete values of the twisting parameter $\nu$ one obtains representations belonging to the discrete series and their continuations. Typically these representations arise as submodules of the Verma modules obtained by the action of noncompact generators on the spherical vectors of quasiconformal group actions. For the quasiconformal groups of
Euclidean Jordan algebras these special representations include the quaternionic discrete representations and their continuations [36, 57], which can be realized over the space of holomorphic functions of complexified quasiconformal coordinates. These holomorphic coordinates can be identified with the natural complex coordinates of the twistor spaces associated with the quaternionic symmetric spaces

$$\frac{QConf(J)}{Conf(J) \times SU(2)}$$

when $J$ is Euclidean. For rank two quaternionic quasiconformal groups $SU(2,1)$ and $G_{2(2)}$ these representations were studied in [36].

5. Spherical Vectors of Quasiconformal Groups associated with Split Non-Euclidean Jordan algebras of Degree Three

A Jordan algebra $J$ of degree three admits three mutually orthogonal irreducible idempotents $P_1, P_2, P_3$:

$$P_i \circ P_j = \delta_{ij} P_i \quad (5.0.1)$$

$$Tr(P_i) = 1 \quad i, j, \ldots = 1, 2, 3$$

As stated earlier in our labelling of the basis elements of split Jordan algebras of degree three we identify $e_i$ with $P_i$ for $i = 1, 2, 3$. By the action of the automorphism group $Aut(J)$ one can “diagonalize” a general element $x \in J$

$$Aut(J) : \quad x \longrightarrow x_D = \lambda_1 e_1 + \lambda_2 e_2 + \lambda_3 e_3 \quad (5.0.2)$$

The cubic norm of $x$ is therefore

$$N(x) = 3\sqrt{3}(\lambda_1 \lambda_2 \lambda_3) \quad (5.0.3)$$

This holds true for Euclidean as well as for split non-Euclidean Jordan algebras of degree three (assuming $n_V \geq 3$). The quasiconformal group of the Jordan subalgebra generated by the irreducible idempotents is $SO(4, 4)$ which is the U-duality group of the STU model and was studied in [17]. This Jordan subalgebra is isomorphic to the Euclidean algebra $(\mathbb{R} \oplus \Gamma_{(1,1)})$, which is a subalgebra of all the generic family of Jordan algebras $(\mathbb{R} \oplus \Gamma_{(m,n)})$ for $m, n > 1$. The simple split non-Euclidean Jordan algebras all have $J_3^\mathbb{R}$ as a subalgebra and hence its quasiconformal group $F_{4(4)}$ is a subgroup of the split exceptional quasiconformal groups $E_{6(6)}$, $E_{7(7)}$ and $E_{8(8)}$ of the split simple Jordan algebras $J_3^{\mathbb{C}_2}$, $J_3^{\mathbb{H}_2}$, $J_3^{\mathbb{O}_2}$. Now the quasiconformal groups of all Euclidean Jordan algebras of degree three are of the quaternionic real form, in particular the groups $SO(4, 4)$ and $F_{4(4)}$.

Unitary representations induced by the action of quaternionic quasiconformal groups with unitary character $\nu$ include the quaternionic discrete series representations of Gross and Wallow [46] as was shown explicitly for rank two cases in [36]. The explicit expressions for the
spherical vectors of quasiconformal realizations of $SU(2,1)$ and $G_{2(2)}$ were essential to establish this result [36]. The quaternionic discrete series representations and their continuations appear as submodules in the Verma modules generated by the action of noncompact generators on the spherical vectors for special discrete values of the parameter $\nu$ that is the twisting parameter in the quasiconformal group action. The spherical vectors for all quaternionic quasiconformal groups defined by Euclidean Jordan algebras of degree three were given in [36]. In this section we shall extend these results to quasiconformal groups of all split non-Euclidean Jordan algebras of degree three. The study of discrete series representations induced by the corresponding quasiconformal group actions will be subjects of separate studies.

Now the spherical vector of quasiconformal group action of $QConf(J)$ twisted by a unitary character $\nu$ is a function $\Phi_{\nu}(p, q, x)$ of $2n_v + 3$ variables $q_0, q_I, p^0, p_I$ and $x$ that is annihilated by all the generators $\mathfrak{K}_M$ of the maximal compact subgroup $K$ of $QConf(J)$:

$$\mathfrak{K}_M \Phi_{\nu}(p, q, x) = 0 \quad (5.0.4)$$

In [47] we presented the spherical vectors of all quasiconformal groups associated with Euclidean Jordan algebras of degree three. The spherical vector of a general quasiconformal group $QConf(J)$ associated with a split Non-Euclidean Jordan algebra $J$ can be written in the form:

$$\Phi_{\nu}(p, q, x) = [(1 + x^2 + I_2^S - I_4)^2 - (I_2^S)^2 + 8I_4 + \frac{1}{2}I_6^S + 8xJ_4^S + \frac{4}{81}H_4^S]^\frac{1}{2} \quad (5.0.5)$$

where

$$I_2^S = (p^0)^2 + (q_0)^2 + p^I\eta_IJp^J + q_I\eta_IJq_J \quad (5.0.6)$$

$$I_4 = (p^0 q_0 - p^I q_I)^2 - \frac{4}{3}C_{IJK}p^Jp^KC^{LM}q_Lq_M + \frac{4}{3\sqrt{3}}p^0C_{IJK}q_Iq_Jq_K + \frac{4}{3\sqrt{3}}q_0C_{IJK}p^Ip^Jp^K \quad (5.0.7)$$

$$J_4^S = \frac{1}{4} \left( p^0 \frac{\partial I_4}{\partial q_0} - q_0 \frac{\partial I_4}{\partial p^0} + q_I\eta_I^J \frac{\partial I_4}{\partial p^J} - p^I\eta_I^J \frac{\partial I_4}{\partial q_J} \right) \quad (5.0.8)$$

$$I_6^S = \left( \frac{\partial I_4}{\partial p^0} \right)^2 + \left( \frac{\partial I_4}{\partial q_0} \right)^2 + \left( \frac{\partial I_4}{\partial p^I} \right) \eta_I^J \left( \frac{\partial I_4}{\partial p^J} \right) + \left( \frac{\partial I_4}{\partial q_I} \right) \eta_I^J \left( \frac{\partial I_4}{\partial q_J} \right) + 4I_4^2 \quad (5.0.9)$$

$$H_4^S = 27\eta_I^J \left( (p^#)_I - \sqrt{3}p^0 q_I \right) \left( (p^#)_J - \sqrt{3}p^0 q_J \right) + 27\eta_I^J \left( (q^#)_I - \sqrt{3}q_0p^I \right) \left( (q^#)_J - \sqrt{3}q_0p^J \right) + 54 \left( (q^#)_I - \sqrt{3}q_0p^I \right) \left( (p^#)_I - \sqrt{3}p^0 q_I \right) + C_4^S(J) \quad (5.0.10)$$

where $(p^#)_I = C_{IJK}p^Jp^K$ and $(q^#)_I = C_{IJK}q_Jq_K$. $C_4^S(J)$ is the “correction” term that vanishes when restricted to the subalgebra $SO(4,4)$ and has a different form for simple Jordan
algebras and non-simple ones. For simple split non-Euclidean Jordan algebras $J$ of degree three the quartic correction term $C_4^S(J)$ is given by

$$C_4^S(J_3^{hS}) = 81 \left( Tr \left[ M_0(p) \circ \tilde{M}_0(q) \right] \right)^2 + \frac{81}{2} \left. Tr \left[ M_0(p)^2 \right] \right. Tr \left[ \tilde{M}_0(q)^2 \right]$$

$$-243 \left. Tr \left[ \{M_0(p), \tilde{M}_0(q), M_0(p) \circ \tilde{M}_0(q) \} \right] \right. \quad (5.0.11)$$

where

$$M_0(q) = M(q) - \frac{1}{3} Tr M(q) \quad (5.0.12)$$

$$M(q) = e^I q_I \quad (5.0.13)$$

and $\tilde{M}(q) = M^*(q)$ where $*$ is the conjugation that replaces the "imaginary" units $j^S_\mu$ that square to $+1$ by $-j^S_\mu$ in the underlying split composition algebra $A^S$. $\{A, B, C\}$ denotes the Jordan triple product

$$\{A, B, C\} = A \circ (B \circ C) + C \circ (B \circ A) - (A \circ C) \circ B \quad (5.0.14)$$

For special Jordan algebras with the Jordan product

$$A \circ B = \frac{1}{2}(AB + BA)$$

one finds

$$\{A, B, A\} = ABA \quad (5.0.15)$$

Therefore for Jordan algebras $J_3^{CS}$ and $J_3^{hS}$ the term $C_4^S(J)$ can be written as

$$C_4^S(J_3^{hS}) = 81 \left( Tr \left[ M_0(p) \tilde{M}_0(q) \right] \right)^2 + \frac{81}{2} \left. Tr \left[ M_0(p)^2 \right] \right. Tr \left[ \tilde{M}_0(q)^2 \right]$$

$$-243 \left. Tr \left[ M_0(p) \tilde{M}_0(q) M_0(p) \tilde{M}_0(q) \right] \right. \quad (5.0.16)$$

For the generic nonsimple Jordan algebras $(\mathbb{R} \oplus \Gamma_{(n,m)})$ $(m, n \geq 1)$ of degree three the cubic form is

$$\mathcal{N}(q) = C^{ijIK} q_i q_j q_K = \frac{3\sqrt{3}}{2} q_1 [2q_2 q_3 - \eta^{ij} q_i q_j] \quad (5.0.17)$$

and the quartic correction term $C_4^S$ that appears in $H_4^S$ is given by

$$C_4^S(\mathbb{R} \oplus \Gamma_{(n,m)}) = -\frac{81}{2} \left\{ (p^2 - p^3)(q_2 - q_3) + 2p^I q_I \right\}^2$$

$$+ \frac{81}{2} \left\{ (p^2 - p^3)^2 + 2\eta^{ij} p^i p^j \right\} \left\{ (q_2 - q_3)^2 + 2\eta^{ij} q_i q_j \right\} \quad (5.0.18)$$

where $\hat{I}, \hat{J}, ... = 4, 5, ..., (m + n + 1)$. 

- 25 -
We should perhaps recall that the Euclidean Jordan algebra $J^S_3$ is a subalgebra of all simple split Jordan algebras of degree three. An element of $J^S_3$ can be written as

$$M(p) = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} p^1 & p^6 & p^5 \\ p^6 & \sqrt{2} p^2 & p^4 \\ p^5 & p^4 & \sqrt{2} p^3 \end{pmatrix}$$  \hspace{1cm} (5.0.19)$$

and its cubic norm is simply

$$N(M(p)) = 3\sqrt{3} \text{Det} M = C_{IJK} p^I p^J p^K$$  \hspace{1cm} (5.0.20)

$$= 3\sqrt{3} \left\{ p^1 p^2 p^3 - \frac{1}{2} \left[ p^1 (p^4)^2 + p^2 (p^5)^2 + p^3 (p^6)^2 \right] + \frac{1}{\sqrt{2}} p^4 p^5 p^6 \right\}$$

5.1 Quasiconformal Group $E_{8(8)}$

The quasiconformal group associated with the split exceptional Jordan algebra $J^O_3$ is the split exceptional group $E_{8(8)}$. A general element of $J^O_3$ can be written as

$$M(p) = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} p^1 & P_6^6 & P_5^5 \\ P_6^6 & P_5^5 & \sqrt{2} p^2 \\ P_5^5 & P_4^4 & \sqrt{2} p^3 \end{pmatrix}$$  \hspace{1cm} (5.1.21)$$

where $P_4^4$, $P_5^5$ and $P_6^6$ are split octonions. The cubic norm of $M(p)$ is normalized to be

$$N(M(p)) = 3\sqrt{3} \left\{ p^1 p^2 p^3 - \frac{1}{2} \left[ p^1 P_4^4 P_5^5 + p^2 P_5^5 P_6^6 + p^3 P_6^6 P_5^5 \right] + \frac{1}{\sqrt{2}} \text{Re}(P_4^4 P_5^5 P_6^6) \right\}$$  \hspace{1cm} (5.1.22)$$

where $\text{Re}(X_S)$ denotes the real part of $X_S \in O_S$ and $\bar{X}_S$ is the octonion conjugate of $X_S$. If we expand the elements $P_4^4$, $P_5^5$ and $P_6^6$ in terms of their real components

$$P_4^4 = p^4 + p^{4+3i} j_i + p^{4+3\mu} j_\mu$$
$$P_5^5 = p^5 + p^{5+3i} j_i - p^{5+3\mu} j_\mu$$
$$P_6^6 = p^6 + p^{6+3i} j_i + p^{6+3\mu} j_\mu$$

$$\bar{P}_4^4 = p^4 - p^{4+3i} j_i + p^{4+3\mu} j_\mu$$
$$\bar{P}_5^5 = p^5 - p^{5+3i} j_i - p^{5+3\mu} j_\mu$$
$$\bar{P}_6^6 = p^6 - p^{6+3i} j_i - p^{6+3\mu} j_\mu$$  \hspace{1cm} (5.1.23)$$

where the indices $i$ and $\mu$ are summed over with $i$ running over 1, 2, 3 and $\mu$ running over
4, 5, 6, 7, we can write the cubic norm as

\[
\mathcal{N}(M(p)) = 3\sqrt{3}\left\{ p^1p^2p^3 - \frac{1}{2}p^1[(p^4)^2 + p^{1+3i}p^{4+3i} - p^{4+3\mu}p^{4+3\mu}] \\
- \frac{1}{2}p^2[(p^5)^2 + p^{5+3i}p^{5+3i} - p^{5+3\mu}p^{5+3\mu}] - \frac{1}{2}p^3[(p^6)^2 + p^{6+3i}p^{6+3i} - p^{6+3\mu}p^{6+3\mu}] \\
+ \frac{1}{\sqrt{2}}\left( p^4p^5p^6 - p^4\left( p^{5+3i}p^{6+3i} - p^{5+3\mu}p^{6+3\mu} \right) - p^5\left( p^{4+3i}p^{6+3i} - p^{4+3\mu}p^{6+3\mu} \right) \right) - \frac{1}{\sqrt{2}}\epsilon_{ijk}p^{(4+3i)p^{5+3j}p^{6+3k}} \right\} (5.1.24)
\]

With the above labelling of the basis elements we have

\[
\eta_{AB} = \delta_{AB} \tag{5.1.25} \\
\eta_{RS} = -\delta_{RS} \\
\eta_{AR} = 0
\]

where \( A, B, \ldots = 1, 2, \ldots, 15 \) and \( R, S, \ldots = 16, 17, \ldots, 27 \). The conjugate elements \( \tilde{M}(p) \) of \( J_{3}^{Q_{S}} \) obtained by conjugation \( * \) is given by

\[
M(p) = \frac{1}{\sqrt{2}}\left( \sqrt{2}p^1 (P_8^S)^* (P_8^S)^* (P_{16}^S)^* \right) \\
\left( P_8^S)^* \sqrt{2}p^2 (P_{1}^4)^* \right) \\
\left( P_{16}^S)^* (P_{16}^S)^* \sqrt{2}p^3 \right) \tag{5.1.26}
\]

where \( * \) is the conjugation under which

\[
(j_i)^* = j_i \\
(j_8)^* = -j_8
\]

where \( i = 1, 2, 3 \) and \( \mu = 4, 5, 6, 7 \). Thus we find

\[
Tr M(p) \circ \tilde{M}(p) = \sum_{l=1}^{27} p^l p^l
\]

The explicit expressions for the generators of quasiconformal group \( E_{8(8)} \) and its spherical vector are obtained by substituting the expressions for the cubic form \( 5.1.24 \) and the metric \( \eta_{I,J} \) in \( 4.1.8-4.1.18 \) and in \( 6.0.3 \). The generators of the maximal compact subgroup \( SO(16) \)
SU(8) subgroup of SO(16) generated by \((R_A^R - R_B^R), (R_S^S - R_B^S), (R_A^S + R_S^A), (R_A + R_A^R)\) and \((R_R - R_R^R)\) act linearly in the quasiconformal action of \(E_8(8)\) on the 57 dimensional space with coordinates \(p^0, p^I, q_0, q_I\) and \(x\). Thus we shall refer to the coset space

\[
\mathcal{K}(QConf(J_{3}^{D_S}) = \frac{SO(16)}{SU(8)}
\]

as the “quasiconformal compactification” of this 57 dimensional space [58]. As explained in detail in [19] one can embed the subgroup \(E_7(7)\) inside \(E_8(8)\) in essentially three different ways. The \(E_7(7)\) subgroup generated by the grade zero generators (with respect to \(D\)) acts linearly. In addition we have two different subgroups, which we label as \(E_7^q(7)\) and \(E_7^p(7)\) that act as the nonlinear conformal group of \(J_{3}^{D_S}\) on the coordinates and momenta, respectively. The conformal compactification of the corresponding 27 dimensional space is [58]

\[
\mathcal{K}(Conf(J_{3}^{D_S}) = \frac{SU(8)}{USp(8)}
\]

It is interesting to compare \(E_8(8)\) as the quasiconformal group associated with the split exceptional Jordan algebra with \(E_8(-24)\) as the quasiconformal group of the Euclidean exceptional Jordan algebra defined over the division algebra of real octonions. \(E_8(-24)\) has the maximal compact subgroup \(E_7 \times SU(2)\). The quasiconformal action \(E_8(-24)\) extends naturally to a holomorphic quasiconformal action on the complex coordinates of the corresponding twistor space [36]

\[
\frac{E_8(-24) \times SU(2)}{E_7 \times SU(2) \times U(1)} = \frac{E_8(-24)}{E_7 \times U(1)}
\]
The quasiconformal compactification of the 57 dimensional space on which $E_{8(-24)}$ acts is the coset space

$$K(QConf(J_3^{op})) = \frac{E_7 \times SU(2)}{E_6 \times U(1)} \quad (5.1.30)$$

The subgroup $E_{7(-25)}$ has similarly three inequivalent embeddings inside $E_{8(-24)}$. The conformal compactification of the 27 dimensional space on which $E_{7(-25)} = Conf(J_3^{op})$ acts nonlinearly is the coset space

$$K(Conf(J_3^{op})) = \frac{E_6}{F_4} \times S^1 \quad (5.1.31)$$

### 5.2 Quasiconformal Group $E_{7(7)}$

Quasiconformal group associated with the Jordan algebra $J_3^{op}$ over the split quaternions $\mathbb{H}_S$ is $E_{7(7)}$. A general element of $J_3^{op}$ can be written in the form

$$M(p) = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}p^1 & P_6^6 & P_5^5 \\ P_6^6 & \sqrt{2}p^2 & P_4^4 \\ P_5^5 & P_4^4 & \sqrt{2}p^3 \end{pmatrix} \quad (5.2.32)$$

where $P_4^4$, $P_5^5$, and $P_6^6$ are now split quaternions. The cubic norm of $M(p)$ is given by

$$N(M(p)) = 3\sqrt{3}(p^1p^2p^3 - \frac{1}{2}(p^1P_6^6P_6^6 + p^2P_5^5P_5^5 + p^3P_4^4P_4^4) + \frac{1}{\sqrt{2}}Re(P_4^4P_5^5P_6^6)) \quad (5.2.33)$$

where $Re(X_S)$ denotes the real part of $X_S \in \mathbb{H}_S$ and $\bar{X}_S$ is the quaternion conjugate of $X_S$.

If we expand the elements $P_4^4$, $P_5^5$, and $P_6^6$ in terms of their components

$$P_4^4 = p^4 + p^7j_1 + p^{4+3m}j_m$$
$$P_5^5 = p^4 - p^7j_1 - p^{4+3m}j_m$$
$$P_6^6 = p^5 + p^8j_1 + p^{5+3m}j_m$$
$$\bar{P}_5^5 = p^5 - p^8j_1 - p^{5+3m}j_m$$
$$P_6^6 = p^6 + p^9j_1 + p^{6+3m}j_m$$
$$\bar{P}_6^6 = p^6 - p^9j_1 - p^{6+3m}j_m \quad (5.2.34)$$

where the indices $m, n, ..$ are summed over and take values 2, 3.
The cubic norm $N(M(p))$ of $M(p)$ can thus be written as

$$N(M(p)) = 3\sqrt{3}\left\{ p^1 p^2 p^3 - \frac{1}{2} p^1 [(p^4)^2 + (p^7)^2 - p^{4+3m} p^{4+3m}] - \frac{1}{2} p^2 [(p^5)^2 + (p^8)^2 - p^{5+3m} p^{5+3m}] - \frac{1}{2} p^3 [(p^6)^2 + (p^9)^2 - p^{6+3m} p^{6+3m}] \right\}$$

$$+ \frac{1}{\sqrt{2}} \left\{ p^4 p^5 p^6 - p^4 \left( p^8 - p^{(5+3m)} p^{(6+3m)} \right) - p^5 \left( p^7 - p^{(4+3m)} p^{(6+3m)} \right) - p^6 \left( p^7 - p^{(4+3m)} p^{(5+3m)} \right) \right\} + \frac{1}{\sqrt{2}} \epsilon_{1mn} p^7 p^{5+3m} p^{6+3n} + \frac{1}{\sqrt{2}} \epsilon_{m1n} p^4+3m p^{6+3n} + \frac{1}{\sqrt{2}} \epsilon_{m1n} p^4+3m p^{9+3n} \right\}$$

With the above labelling of the basis elements we have

$$\eta_{AB} = \delta_{AB} \quad (5.2.36)$$

$$\eta_{RS} = -\delta_{RS}$$

$$\eta_{AR} = 0$$

where $A, B, .. = 1, 2, ..., 9$ and $R, S, .. = 10, 11, ..., 15$. The conjugate elements $\tilde{M}(p)$ of $J_3^{CS}$ obtained by conjugation $\ast$ is given by

$$M(p) = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} p^1 (P^8)^* (P^5)^* \\ (P^8)^* \sqrt{2} p^2 (P^4)^* \\ (P^5)^* (P^5)^* \sqrt{2} p^3 \end{pmatrix}$$

where under the conjugation $\ast$ we have

$$j_1^\ast = j_1$$

$$j_m^\ast = -j_m \quad (5.2.38)$$

The maximal compact subgroup of $E_{7(7)}$ is $SU(8)$ and its generators can be obtained by restricting the range of indices in 5.1.27 such that $A, B, .. = 1, 2, ..., 9$ and $R, S, .. = 10, 11, ..., 15$. The quasi-conformal compactification of the 33 dimensional space on which $E_{7(7)}$ acts is

$$\mathcal{K}(QConf(J_3^{CS}) = \frac{SU(8)}{SU(4) \times SU(4)} \quad (5.2.39)$$

The subgroup $SO(6,6)$ has three different embeddings in $E_{7(7)}$, two of which are conformal acting on 15 coordinates or momenta, respectively. The conformal compactification of the 15 dimensional space on which $SO(6,6)$ acts is

$$\mathcal{K}(Conf(J_3^{HS}) = \frac{SU(4) \times SU(4)}{SU(4)} \quad (5.2.40)$$
We recall that for the Euclidean Jordan algebra \( J^H_3 \) the associated quasiconformal group is \( E_{7(-5)} \) and the quasiconformal compactification of the corresponding 33 dimensional space is \( K(\text{QConf}(J^H_3)) = SO(12) \times SU(2) / SU(6) \times U(1) \) (5.2.41)

The quasiconformal group \( E_{7(-5)} \) has a subgroup \( SO^*(12) \) which acts on the underlying Jordan algebra \( J^H_3 \) as a conformal group. The conformal compactification of the corresponding 15 dimensional space is \( K(\text{Conf}(J^H_3)) = SU(6) \times USp(6) \times S^1 \) (5.2.42)

5.3 Quasiconformal Group \( E_{6(6)} \)

Quasiconformal group associated with the Jordan algebra \( J^C_3 \) over the split complex numbers \( \mathbb{C}_S \) is \( E_{6(6)} \). A general element of \( J^C_3 \) can be written in the form

\[
M(p) = \frac{1}{\sqrt{2}} \begin{pmatrix}
\sqrt{2}p^1 & P^6_S & P^5_S \\
\bar{P}^6_S & \sqrt{2}p^2 & P^4 \\
\bar{P}^5_S & P^4 & \sqrt{2}p^3
\end{pmatrix}
\]

where \( P^4_S, P^5_S \) and \( P^6_S \) are now split complex numbers. The cubic norm of \( M(p) \) is given by

\[
\mathcal{N}(M(p)) = 3\sqrt{3}\{p^1 p^2 p^3 - \frac{1}{2}(p^1 P^4_S \bar{P}^4_S + p^2 P^5_S \bar{P}^5_S + p^3 P^6_S \bar{P}^6_S) + \frac{1}{\sqrt{2}} Re(P^4_S P^5_S P^6_S)\}
\]

where \( Re(X_S) \) denotes the real part of \( X_S \in \mathbb{C}_S \) and \( \bar{X}_S \) is the complex conjugate of \( X_S \). If we expand the elements \( P^4_S, P^5_S \) and \( P^6_S \) in terms of their components

\[
\begin{align*}
P^4_S &= p^4 + p^7 j^s \\
\bar{P}^4_S &= p^4 - p^7 j^s \\
P^5_S &= p^5 + p^8 j^s \\
\bar{P}^5_S &= p^5 - p^8 j^s \\
P^6_S &= p^6 + p^9 j^s \\
\bar{P}^6_S &= p^6 - p^9 j^s
\end{align*}
\]

where \( j^s \) is the split “imaginary” unit that squares to +1

\[
(j^s)^2 = 1
\]
The cubic norm $\mathcal{N}(M(p))$ of $M(p)$ can thus be written as
\[
\mathcal{N}(M(p)) = 3\sqrt{3}\left\{p^1p^2p^3 - \frac{1}{2}p^1[(p^4)^2 - (p^7)^2] - \frac{1}{2}p^2[(p^5)^2 - (p^8)^2] - \frac{1}{2}p^3[(p^6)^2 - (p^9)^2] + \frac{1}{\sqrt{2}}\left\{p^4p^5p^6 + p^4(p^8p^9) + p^5(p^7p^9) + p^6(p^7p^8)\right\}\right\}
\]

With the above labelling of the basis elements we have
\[
\eta_{AB} = \delta_{AB} \quad \text{(5.3.47)}
\]
\[
\eta_{RS} = -\delta_{RS}
\]
\[
\eta_{AR} = 0
\]

where $A, B, .. = 1, 2, ..., 6$ and $R, S, .. = 7, 8, 9$. The conjugate elements $\tilde{M}(p)$ of $J^\mathbb{H}_3$ obtained by conjugation $\ast$ is given by
\[
M(p) = \frac{1}{\sqrt{2}}\begin{pmatrix}
\sqrt{2}p^1 & (P^6_S)^* & (P^5_S)^* \\
(P^6_S)^* & \sqrt{2}p^2 & (P^4_S)^* \\
(P^5_S)^* & (P^4_S)^* & \sqrt{2}p^3
\end{pmatrix}
\]

where under the conjugation $\ast$ we have
\[
(j^*)^* = -(j^*) \quad \text{(5.3.49)}
\]

The maximal compact subgroup of $E_{6(6)}$ is $USp(8)$ and its generators can be obtained by restricting the range of indices in \[5.1.27\] such that $A, B, .. = 1, 2, ..., 6$ and $R, S, .. = 7, 8, 9$. The quasiconformal compactification of the 21 dimensional space on which $E_{6(6)}$ acts is
\[
\mathcal{K}(\text{QConf}(J^\mathbb{C}_3)) = \frac{USp(8)}{SU(4)} \quad \text{(5.3.50)}
\]

The subgroup $SL(6, \mathbb{R})$ has three different embeddings in $E_{6(6)}$, two of which are conformal acting on 9 coordinates or momenta, respectively. The conformal compactification of the corresponding 9 dimensional space on which $SL(6, \mathbb{R})$ acts is
\[
\mathcal{K}(\text{Conf}(J^\mathbb{C}_3)) = \frac{SO(6)}{SO(3) \times SO(3)} \quad \text{(5.3.51)}
\]

We recall that for the Euclidean Jordan algebra $J^\mathbb{C}_3$ the associated quasiconformal group is $E_{6(2)}$ and the quasiconformal compactification of the corresponding 21 dimensional space is
\[
\mathcal{K}(\text{QConf}(J^\mathbb{C}_3)) = \frac{SU(6) \times SU(2)}{SU(3) \times SU(3) \times U(1)} \quad \text{(5.3.52)}
\]
The quasiconformal group $E_{6(2)}$ has a subgroup $SU(3, 3)$ which acts on the underlying Jordan algebra $J_3^C$ as a conformal group. The conformal compactification of the corresponding 9 dimensional space is

$$
\mathcal{K}(Conf(J_3^C)) = \frac{SU(3) \times SU(3)}{SU(3)} \times S^1
$$

(5.3.53)

### 5.4 Quasiconformal Group $SO(n + 3, m + 3)$

For the generic nonsimple Jordan algebras $(\mathbb{R} \oplus \Gamma_{(n,m)})$ of degree three the cubic form is

$$
\mathcal{N}(q) = C^{ijk} q_i q_j q_k = \frac{3\sqrt{3}}{2} q_1 [2q_2 q_3 - \eta^{ij} q_i q_j]
$$

(5.4.54)

where $\hat{i}, \hat{j}, ... = 4, 5, ..., (m + n + 1)$ and

$$
\eta^{ij} = \delta^{ij}, \hat{i}, \hat{j} = 4, 5, ..., m + 2
$$

(5.4.55)

and the associated quasiconformal group is $SO(n + 3, m + 3)$. The quartic correction term $C_4^S$ that appears in $H_4^S$ in the spherical vectors is given by

$$
C_4^S(\mathbb{R} \oplus \Gamma_{(n,m)}) = -\frac{81}{2} \left\{ (p^2 - p^3)(q_2 - q_3) + 2p^i q_i \right\}^2 + \frac{81}{2} \left\{ (p^2 - p^3)^2 + 2\eta_{ij} p^i q_j \right\} \left\{ (q_2 - q_3)^2 + 2\eta^{ij} q_i q_j \right\}
$$

(5.4.56)

and the full metric $\eta_{ij}$ is given by

$$
\eta_{AB} = \delta_{AB}, \text{ for } A, B, ... = 1, 2, ..., m + 2
$$

$$
\eta_{RS} = -\delta_{RS}, \text{ for } R, S, ... = m + 3, m + 4, ..., m + n + 1
$$

(5.4.57)

The quasiconformal compactification of the $(2n + 2m + 5)$ dimensional space on which $SO(n + 3, m + 3)$ is realized as the quasiconformal group is

$$
\mathcal{K}(QConf(\mathbb{R} \oplus \Gamma_{(n,m)})) = \frac{SO(n + 3) \times SO(m + 3)}{SO(n + 1) \times SO(m + 1) \times SO(2)}
$$

(5.4.58)

The subgroup $SO(m + 1, n + 1) \times SO(2, 1)$ can be embedded in $SO(n + 3, m + 3)$ in three inequivalent ways. Two of these embeddings act nonlinearly as conformal groups on the coordinates and momenta, respectively. The conformal compactification of the $(m + n + 1)$ dimensional space on which $SO(m + 1, n + 1) \times SO(2, 1)$ acts via conformal transformations is

$$
\mathcal{K}(Conf(\mathbb{R} \oplus \Gamma_{(n,m)})) = \frac{SO(m + 1) \times SO(n + 1)}{SO(m) \times SO(n)} \times S^1
$$

(5.4.59)

For Euclidean Jordan algebras $(\mathbb{R} \oplus \Gamma_{(1,m)})$ the quasiconformal group is $SO(4, m + 3)$ and the conformal group is $SO(2, m + 1) \times SO(2, 1)$ leading to the following compactified spaces

$$
\mathcal{K}(QConf(\mathbb{R} \oplus \Gamma_{(1,m)})) = \frac{SO(4) \times SO(m + 3)}{SO(2) \times SO(m + 1) \times SO(2)}
$$

(5.4.60)

$$
\mathcal{K}(Conf(\mathbb{R} \oplus \Gamma_{(1,m)})) = \frac{SO(m + 1)}{SO(m)} \times S^1 \times S^1
$$

(5.4.61)
6. Exceptional $N = 2$ MESGT, $N = 8$ Supergravity and Jordan Algebras of Degree Four

As explained above the U-duality symmetry groups of the maximal supergravity in 5, 4 and 3 dimensions are simply the Lorentz (reduced structure), conformal and quasiconformal groups of the split exceptional Jordan algebra $J_{3}^{OS}$, which is not Euclidean. On the other hand the corresponding U-duality groups of the exceptional $N = 2$ supergravity are the Lorentz, conformal and quasiconformal groups of the real exceptional Jordan algebra $J_{3}^{O}$ which is Euclidean. The scalar manifold of the exceptional theory in five dimensions is simply

$$M_{5}(J_{3}^{O}) = \frac{Str_{0}(J_{3}^{O})}{Aut(J_{3}^{O})} = \frac{E_{6(-26)}}{F_{4}}$$

However the scalar manifold of the maximal supergravity is

$$\frac{E_{6(6)}}{USp(8)}$$

so that the maximal compact subgroup is not the automorphism group of the split exceptional Jordan algebra. Remarkably, there is a formulation of the exceptional Jordan algebras in terms of degree four Jordan algebras in which the situation gets reversed. As was shown in [tters] the exceptional supergravity can also be formulated in terms of Lorentzian Jordan algebra $J_{(1,3)}^{H}$ of $4 \times 4$ quaternionic matrices that are Hermitian with respect to a Lorentzian metric. This is achieved by the mapping between the traceless elements, which we denote as $J_{(1,3)}^{H}$, of $J_{(1,3)}^{H}$ and the elements of the exceptional Jordan algebra $J_{3}^{O}$:

$$x \in J_{3}^{O} \implies X \in J_{(1,3)}^{H} \quad (6.0.1)$$

such that the cubic norm $N(x)$ of $x$ is equal to the trace of $X^{3}$:

$$N(x) = Tr(X^{3}) \quad (6.0.2)$$

Now the automorphism group of $J_{(1,3)}^{H}$ is $USp(6,2)$ which is the manifest symmetry of the trace form. Hence the trace of $X^{3}$ has “hidden” extra symmetries which extend $USp(6,2)$ to $E_{6(-26)}$, which is the Lorentz (reduced structure) group of $J_{3}^{O}$. However, the Lorentz (reduced structure) group $SU^{*}(8)$ of $J_{(1,3)}^{H}$ is not a symmetry of the exceptional MESGT in five dimensions.

Similarly there is a mapping between the elements $y$ of the split exceptional Jordan algebra $J_{3}^{OS}$ and the traceless elements $Y$ of Euclidean Jordan algebra $J_{4}^{H}$ of $4 \times 4$ Hermitian matrices over the division algebra of quaternions $\mathbb{H}$ [tters]

$$y \in J_{3}^{OS} \implies Y \in J_{4}^{H} \quad (6.0.3)$$

such that one finds

$$N(y) = Tr(Y^{3}) \quad (6.0.4)$$
The automorphism group $USp(8)$ of $J_4^{\mathbb{H}}$ is the manifest symmetry of the trace form. Again extra hidden symmetries of $\text{Tr}(Y^3)$ extend it to the Lorentz (reduced structure) group $E_{6(6)}$ of $J_4^{\mathbb{O}_S}$. However the scalar manifold of the maximal supergravity in five dimensions is

$$
\mathcal{M}_5(N = 8) = \frac{\text{Str}_0(J_3^{\mathbb{O}_S})}{\text{Aut}(J_4^{\mathbb{H}})} = \frac{E_{6(6)}}{USp(8)} \quad (6.0.5)
$$

The Lorentz (reduced) structure group $SU^*(8)$ of $J_4^{\mathbb{H}}$ is not a symmetry of maximal supergravity in five dimensions. In four dimensions the scalar manifold of maximal supergravity is

$$
\mathcal{M}_4(N = 8) = \frac{\text{Conf}(J_3^{\mathbb{O}_S})}{\text{Str}_0(J_4^{\mathbb{H}})} = \frac{E_7(7)}{SU(8)} \quad (6.0.6)
$$

where $\text{Str}_0(J_4^{\mathbb{H}})$ denotes the compact real form of the Lorentz (reduced structure) group of $J_4^{\mathbb{H}})$. In three dimensions one has the scalar manifold

$$
\mathcal{M}_3(N = 8) = \frac{Q\text{Conf}(J_3^{\mathbb{O}_S})}{\text{Conf}(J_4^{\mathbb{H}})} = \frac{E_8(8)}{SO(16)} \quad (6.0.7)
$$

where $\text{Conf}(J)$ refers to the compact real form of the conformal group of $J$.

One can truncate the above correspondences between the real and split exceptional Jordan algebras and $J_4^{\mathbb{H}}(1,3)$ and $J_4^{\mathbb{H}}$, respectively, to correspondences between rank three complex and quaternionic Jordan algebras and rank four real and complex Jordan algebras:

$$
J_3^{\mathbb{C}} \iff J_3^{\mathbb{R}_0}
J_3^{\mathbb{H}} \iff J_3^{\mathbb{C}_0}
J_3^{\mathbb{O}_S} \iff J_4^{\mathbb{R}_0}
J_3^{\mathbb{H}_S} \iff J_4^{\mathbb{C}_0} \quad (6.0.8)
$$

Remarkably the $N = 2$ MESGT theories defined by Lorentzian Jordan algebras $J_4^{\mathbb{H}(1,3)}$ belong to three infinite families of unified MESGT’s in five dimensions defined by Lorentzian Jordan algebras of arbitrary rank \[69\]. Study of quasiconformal groups associated with Lorentzian Jordan algebras will be left to future studies.

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