Geometric Aspects of the Painlevé Equations
PIII(D₆) and PIII(D₇)

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Abstract. The Riemann–Hilbert approach for the equations PIII(D₆) and PIII(D₇) is studied in detail, involving moduli spaces for connections and monodromy data, Okamoto–Painlevé varieties, the Painlevé property, special solutions and explicit Bäcklund transformations.

Key words: moduli space for linear connections; irregular singularities; Stokes matrices; monodromy spaces; isomonodromic deformations; Painlevé equations

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1 Introduction

The aim of this paper is a study of the Painlevé equations PIII(D₆) and PIII(D₇) by means of isomonodromic families in a moduli space of connections of rank two on the projective line. This contrasts the work of Okamoto et al. on these third Painlevé equations, where the Hamiltonians are the main tool. However, there is a close relation between the two points of view, since the moduli spaces turn out to be the Okamoto–Painlevé varieties. We refer only to a few items of the extensive literature on Okamoto–Painlevé varieties. More details on Stokes matrices and the analytic classification of singularities can be found in [11].

A rough sketch of this Riemann–Hilbert method is as follows (see for some background [10] and see for details concerning PI, PII, PIV [8, 9, 12]). The starting point is a family S of differential modules M of dimension 2 over ℂ(z) with prescribed singularities at fixed points of ℙ¹. The type of singularities gives rise to a monodromy set R built out of ordinary monodromy, Stokes matrices and ‘links’. The map S → R associates to each module M ∈ S its monodromy data in R. The fibers of S → R are parametrized by T ≅ ℂ⁺ and there results a bijection S → R × T. The set S has a priori no structure of algebraic variety. A moduli space M over ℂ, whose set of closed points consists of certain connections of rank two on the projective line, is constructed such that S coincides with M(ℂ). There results an analytic Riemann–Hilbert morphism RH : M → R. The fibers of RH are the isomonodromic families which give rise to solutions of the corresponding Painlevé equation. The extended Riemann–Hilbert morphism RH⁺ : M → R × T is an analytic isomorphism. From these constructions the Painlevé property for the corresponding Painlevé equation follows and the moduli space M is identified with an Okamoto–Painlevé space. Special properties of solutions of the Painlevé equations, such as special solutions, Bäcklund transformations etc., are derived from special points of R and the natural automorphisms of S.

The above sketch needs many subtle refinements. One has to construct a geometric monodromy space ˜R (depending on the parameters of the Painlevé equation) which is a geometric quotient of the monodromy data. The ‘link’ involves (multi)summation and in order to avoid
the singular directions one has to replace $T$ by its universal covering $\tilde{T} \cong \mathbb{C}$. In the construction of $\mathcal{M}$, one represents a differential module $M \in \mathbf{S}$ by a connection on a fixed vector bundle of rank two on $\mathbb{P}^1$. This works well for the case $(1, -1/2)$, described in Section 2. In case $(1, -1)$, described in Section 3, this excludes a certain set of reducible modules $M \in \mathbf{S}$. The moduli space of connections $\mathcal{M}$ is replaced by the topological covering $\tilde{\mathcal{M}} = \mathcal{M} \times_T \tilde{T}$. Now the main result is that the extended Riemann–Hilbert morphism $\text{RH}^+ : \tilde{\mathcal{M}} \to \tilde{\mathcal{R}} \times \tilde{T}$ is a well defined analytic isomorphism.

Each family of linear differential modules and each Painlevé equation has its own story. For the family $(1, -, 1/2)$, corresponding to $\text{PIII}(D_7)$, the computations of $\mathcal{R}$, $\mathcal{M}$ and the Bäcklund transformations present no problems. For the resonant case (i.e., $\alpha = \pm 1$ and $\theta \in \mathbb{Z}$, see Sections 2.1, 2.2 and 2.5 for notation and the statement) there are algebraic solutions of $\text{PIII}(D_7)$. The spaces $\mathcal{R}(\alpha)$ with $\alpha = \pm i$ have a special point corresponding to trivial Stokes matrices. This leads to a special solution $q$ for $\text{PIII}(D_7)$ and $\theta \in \frac{1}{2} + \mathbb{Z}$, which is transcendental according to [5]. According to [2], $q$ is a univalent function of $t$ and is a meromorphic at $t = 0$.

For the general case (i.e., $\alpha \neq \beta \pm 1$) of the family $(1, -, 1)$, corresponding to $\text{PIII}(D_6)$, the computations of $\mathcal{R}$, $\mathcal{M}$ present no problems. The formulas for the Bäcklund transformations, derived from the automorphisms of $\mathbf{S}$, have denominators. These originate from the complicated cases $\alpha = \beta \pm 1$ and/or $\alpha = \pm 1$ where reducible connections and/or resonance occur. Isomonodromy for reducible connections produces Riccati solutions and resonance is related to algebraic solutions.

2 The family $(1, -, 1/2)$ and $\text{PIII}(D_7)$

In this section the set $\mathbf{S}$ consists of the (equivalence classes of the) pairs $(M, t)$ of type $(1, -, 1/2)$ (see [10] for the terminology), corresponding to the Painlevé equation $\text{PIII}(D_7)$. The differential module $M$ is given by $\dim M = 2$, the second exterior power of $M$ is trivial, $M$ has two singular points 0 and $\infty$. The Katz invariant $r(0) = 1$ and the generalized eigenvalues at 0 are normalized to $\pm \frac{1}{2}z^{-1}$ with $t \in T = \mathbb{C}^*$. The singular point $\infty$ has Katz invariant $r(\infty) = 1/2$ and generalized eigenvalues $\pm z^{1/2}$. Further $(M, t)$ is equivalent to $(M', t')$ if $M$ is isomorphic to $M'$ and $t = t'$.

The Riemann–Hilbert approach to $\text{PIII}(D_7)$ in this section differs from [10] in several ways. The choice $(1, -, 1/2)$ is made to obtain the classical formula for the Painlevé equation. Further we consider pairs $(M, t)$ rather than modules $M$. This is needed in order to distinguish the two generalized eigenvalues at $z = 0$ and to obtain a good monodromy space $\mathcal{R}$. Finally, the definitions of the topological monodromy and the ‘link’ need special attention.

2.1 The construction of the monodromy space $\mathcal{R} \to \mathcal{P}$

This is rather subtle and we provide here the details. Given is some $(M, t) \in \mathbf{S}$ and we write $\delta_M$ for the differential operator on $M$. First we fix an isomorphism $\phi : \Lambda^2 M \to (\mathbb{C}(z), z^\frac{1}{2} \frac{d}{dz})$.

1. $\mathbb{C}(z) \otimes M$ has a basis $F_1$, $F_2$ such that the operator $\delta_M$ has the matrix $\begin{pmatrix} -\omega & 0 \\ 0 & \omega \end{pmatrix}$ with $\omega = \frac{z^{-1} + \theta}{1 + \theta}$. We require that $\phi(F_1 \wedge F_2) = 1$. Then $F_1$, $F_2$ is unique up to a transformation $(F_1, F_2) \mapsto (\lambda F_1, \lambda^{-1} F_2)$. The solution space $V(0)$ at $z = 0$ has basis $f_1 = e^{-\frac{1}{2}z^{-1} - \theta/2} F_1, f_2 = e^{\frac{1}{2}z^{-1} - \theta/2} F_2$. The formal monodromy and the two Stokes matrices have on the basis $f_1, f_2$ the matrices $\begin{pmatrix} \alpha & 0 \\ 0 & \alpha^{-1} \end{pmatrix}$, $\begin{pmatrix} 1 & 0 \\ c_1 & 1 \end{pmatrix}$, $\begin{pmatrix} 1 & c_2 \\ 0 & 1 \end{pmatrix}$, where $\alpha = e^{\pi i \theta}$. Their product (in this order) is the topological monodromy $\text{top}_0$ at $z = 0$.

2. $\mathbb{C}((z^{-1})) \otimes M$ has a basis $E_1$, $E_2$ such that the operator $\delta_M$ has the matrix $\begin{pmatrix} \frac{1}{z} & 1 \\ z & \frac{1}{z} \end{pmatrix}$ with respect to this basis. Since this differential operator is irreducible, the basis $E_1$, $E_2$ is unique.
One observes that $\alpha$.

The matrix $x$ are nonsingular, affine cubic surfaces with three lines at infinity, given by the equation $R \to P := \alpha$.

The formal monodromy and the Stokes matrix have on the basis $e_{\alpha}$, up to a transformation $(E_1, E_2) \mapsto (\mu E_1, \mu E_2)$ with $\mu \in \mathbb{C}^*$. We require that $\phi(E_1 \wedge E_2) = 1$ and then $\mu \in \{1, -1\}$. The solution space $V(\infty)$ at $z = \infty$ has basis

$$e_1 = \frac{1}{\sqrt{-2}} z^{-1/4} e^{1/2} \left( E_1 + \left( -\frac{1}{2} + z^{1/2} \right) E_2 \right),$$
$$e_2 = \frac{1}{\sqrt{-2}} z^{-1/4} e^{-1/2} \left( E_1 + \left( -\frac{1}{2} - z^{1/2} \right) E_2 \right).$$

The formal monodromy and the Stokes matrix have on the basis $e_1, e_2$ the matrices

$$\begin{pmatrix} 1 & 0 \\ e & 1 \end{pmatrix}.$$ Their product (in this order) is the topological monodromy $top_\infty$ at $z = \infty$.

3. The link $L : V(0) \to V(\infty)$ is a linear map obtained from multisummation at $z = 0$, analytic continuation along a path from 0 to $\infty$ and the inverse of multisummation at $z = \infty$.

The matrix $\begin{pmatrix} \ell_1 & \ell_2 \\ \ell_3 & \ell_4 \end{pmatrix}$ of $L$ with respect to the bases $e_1, e_2$ and $f_1, f_2$ has determinant 1, due to the isomorphism $\phi : \Lambda^2 M \to (\mathbb{C}(z), z^{\frac{d}{2}})$ and the careful choices of the bases. The relation

$$\left( \begin{smallmatrix} \alpha & \alpha c_2 \\ \frac{1}{\alpha c_2} \end{smallmatrix} \right) = \text{top}_0 = L^{-1} \circ \text{top}_\infty \circ L$$
yields $\alpha = -i\ell_1 e + i\ell_2 - i\ell_34 \neq 0$ where $\ell_{ij} := \ell_i \ell_j$.

One observes that $\alpha, c_1, c_2$ are determined by $L$ and $top_\infty$. Thus the affine space, given by the above data and relations, has coordinate ring

$$\mathbb{C} \left[ e, \ell_1, \ell_2, \ell_3, \ell_4, \frac{1}{-\ell_{14} e + \ell_{12} - \ell_{34}} \right] / (\ell_{14} - \ell_{23} - 1).$$

4. The group $G$ generated by the base changes $(e_1, e_2) \mapsto (-e_1, -e_2)$ and $(f_1, f_2) \mapsto (\lambda f_1, \lambda^{-1} f_2)$, acts on this affine space. The monodromy space $\mathcal{R}$ is the categorical quotient by $G$ and has coordinate ring

$$\mathbb{C} \left[ e, \ell_1, \ell_2, \ell_3, \ell_4, \frac{1}{-\ell_{14} e + \ell_{12} - \ell_{34}} \right] / (\ell_{14} - \ell_{23} - 1, \ell_{12} \ell_{34} - \ell_{14} \ell_{23}).$$

This is in fact a geometric quotient. The morphism $\mathcal{R} \to \mathcal{P} = \mathbb{C}^*$ is given by $(e, \ell_1, \ell_2, \ell_3, \ell_4) \mapsto \alpha := -i\ell_{14} e + i\ell_{12} - i\ell_{34} \neq 0$. For a suitable linear change of the variables, the fibers $\mathcal{R}(\alpha)$ of $\mathcal{R} \to \mathcal{P}$ are nonsingular, affine cubic surfaces with three lines at infinity, given by the equation $x_1 x_2 x_3 + x_1^2 + x_2^2 + \alpha x_1 + x_2 = 0$. A detailed calculation resulting in this equation is presented in [10, Section 3.5].

**Lemma 2.1.** The space $\mathcal{R}(\alpha)$ is simply connected.

**Proof.** We remove from $\mathcal{R}(\alpha)$ the line $L := \{(0, 0, x_3) \mid x_3 \in \mathbb{C}\}$ and project onto $\mathbb{C}^2 \setminus S$ by $(x_1, x_2, x_3) \mapsto (x_1, x_2)$. Here $S$ is the union of $\{(0, x_2) \mid x_2 \neq -1\}$ and $\{(x_1, 0) \mid x_1 \neq -\alpha\}$. If $x_1 x_2 \neq 0$, then the fiber is one point. If $x_1 x_2 = 0$, then the fiber is a projective line. Since $\mathbb{C}^2 \setminus S$ is simply connected, $\mathcal{R}(\alpha) \setminus L$ is simply connected. Then $\mathcal{R}(\alpha)$ is simply connected, too. 

**Remark on the differential Galois group.** The differential Galois group of a module $M$, with $(M, \iota) \in S$, can be considered as algebraic subgroup of $GL(V(0))$. It is the smallest algebraic subgroup containing the local differential Galois group $G_0 \subset GL(V(0))$ at $z = 0$ and $L^{-1}G_0 L$, where $G_\infty \subset GL(V(\infty))$ is the local differential Galois group at $z = \infty$. Now $G_0$ is generated (as algebraic group) by the exponential torus $\left\{ \begin{pmatrix} s_1 & 0 \\ 0 & s_1^{-1} \end{pmatrix} \right\}$, the formal monodromy

$$\begin{pmatrix} \alpha & 0 \\ 0 & \alpha^{-1} \end{pmatrix}$$

and the Stokes maps $\begin{pmatrix} 1 & 0 \\ c_1 & 1 \end{pmatrix}, \begin{pmatrix} 1 & c_2 \\ 0 & 1 \end{pmatrix}$. The group $G_\infty$ is (as algebraic group)
generated by the exponential torus \( \left\{ \begin{pmatrix} s_2 & 0 \\ 0 & s_2^{-1} \end{pmatrix} \right\} s_2 \in \mathbb{C}^* \), the formal monodromy \( \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \)

and the Stokes map \( \frac{1}{e} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \). This easily implies that the differential Galois group is \( \text{SL}(2, \mathbb{C}) \).

In particular, \( M \) is irreducible and the same holds for the differential module \( \mathbb{C}(\sqrt{z}) \otimes M \over \mathbb{C}(\sqrt{z}) \) for any \( m \geq 2 \).

The construction needed to define the topological monodromy and the link.

For the definition of the link and the topological monodromies we have to choose nonsingular directions for the two multisummations and a path from \( 0 \) to \( \infty \). At \( z = \infty \) the singular direction does not depend on \( t \in T \) and we can take a fixed nonsingular direction. However, at \( z = 0 \), the singular directions for \( t \in T = \mathbb{C}^* \), \( t = |t|e^{i\phi} \) are \( \phi \) and \( \pi + \phi \) and they vary with \( t \). Thus we cannot use a fixed path from \( 0 \) to \( \infty \). In order to obtain a globally defined map \( L : V(0) \to V(\infty) \) we replace \( T = \mathbb{C}^* \) by its universal covering \( \tilde{T} = \mathbb{C} \to T \), \( \hat{t} \mapsto e^{\hat{t}} \).

The elements of \( \tilde{T} \cong \mathbb{R}_{>0} \times \mathbb{R} \) are written as \( \hat{t} = |t|e^{i\phi} \). Consider the path \( \tilde{z} = re^{i\theta} \), \( 0 < r < \infty \), with \( d(r) = (\phi - \frac{\pi}{2}) \frac{1}{r^2} + \frac{2}{r} \frac{\lambda}{r^2} \) on the universal covering of \( \mathbb{P}^1 \setminus \{0, \infty\} \). Now \( L \) is defined by summation at \( z = 0 \) in the direction \( \phi - \frac{\pi}{2} \), followed by analytic continuation along the above path and finally the inverse of the summation at \( z = \infty \) in the direction \( \frac{\pi}{2} \).

Write \( \tilde{S} = S \times T \tilde{T} \). The elements of \( \tilde{S} \) are the pairs \((M, \hat{t})\) with \( (M, e^{\hat{t}}) \in S \). For the elements in \( S \) the link and the monodromy at \( z = 0 \) are defined as above. Since \( R \) is a geometric quotient, \([10, \text{Theorem 1.9}]\) implies:

The above map \( \tilde{S} \to R \times \tilde{T} \) is bijective.

Fix \( \alpha \in \mathcal{P} = \mathbb{C}^* \). Let \( S(\alpha), \tilde{S}(\alpha) \) be the subsets of \( S \) and \( \tilde{S} \), consisting of the pairs \((M, t)\) and \((M, \hat{t})\) which have \( \begin{pmatrix} \alpha & 0 \\ 0 & \frac{1}{\alpha} \end{pmatrix} \) as formal monodromy at \( z = 0 \).

The map \( \tilde{S}(\alpha) \to R(\alpha) \times \tilde{T} \) is bijective, since \( \tilde{S} \to R \times \tilde{T} \) is bijective.

2.2 The construction of the moduli space \( \mathcal{M}(\theta) \)

Fix \( \theta \) with \( e^{\pi i \theta} = \alpha \). The moduli space \( \mathcal{M}(\theta) \) is obtained by replacing each \((M, t) \in S(\alpha)\) by a certain connection \((\mathcal{V}, \nabla)\) on \( \mathbb{P}^1 \). This connection is uniquely determined by the data: Its generic fiber is \( M; \nabla_z \frac{dz}{z^a} \) is formally equivalent at \( z = 0 \) to \( z^{\frac{d}{dz}} + \begin{pmatrix} \omega & 0 \\ 0 & -\omega \end{pmatrix} \) with \( \omega = \frac{tz^{-1} + \theta}{2} \) and is formally equivalent at \( z = \infty \) to \( z^{\frac{d}{dz}} + \begin{pmatrix} -\frac{3}{4} & 1 \\ z & -1 \end{pmatrix} \). It follows that \( \Lambda^2(\mathcal{V}, \nabla) \) is isomorphic to \( (O(-1), d) \). Since \( (\mathcal{V}, \nabla) \) is irreducible one has that \( \mathcal{V} \cong O \oplus O(-1) \) and the vector bundle \( \mathcal{V} \) is identified with \( Oe_1 + O([-\alpha])e_2 \).

Then \( D := \nabla_z \frac{dz}{z^a} : \mathcal{V} \to O([0] + [\infty]) \otimes \mathcal{V} \) has with respect to \( e_1, e_2 \) the matrix \( \begin{pmatrix} a & b \\ c & -a \end{pmatrix} \) with \( a = a_{-1}z^{-1} + a_0 + a_1z, \ c = c_{-1}z^{-1} + c_0 \) and \( b = b_{-1}z^{-1} + b_0 + b_1z + b_2z^2 \).

The condition at \( z = 0 \) is \( a^2 + bc \in \left( \frac{tz^{-1} + \theta}{2} \right)^2 + \mathbb{C}[[z]] \), equivalently

\[ a_{-1}^2 + b_{-1}c_{-1} = \frac{t^2}{4}, \quad 2a_{-1}a_0 + b_{-1}c_0 + b_0c_{-1} = \frac{t\theta}{2} \].

The condition at \( z = \infty \) is \( a^2 + a + bc = z + \mathbb{C}[[z^{-1}]] \), equivalently

\[ a_0^2 + b_2c_0 = 0, \quad 2a_1a_0 + a_1 + b_2c_{-1} + b_1c_0 = 1. \]

The space, given by the above variables and relations has to be divided by the action of the group \( \{ e_1 \mapsto e_1, e_2 \mapsto \lambda e_2 + (x_0 + x_1z)e_1 \} \) (with \( \lambda \in \mathbb{C}^* \), \( x_0, x_1 \in \mathbb{C} \)) of automorphisms of the vector bundle. Using the standard forms below one sees that this is a good geometric quotient.
A standard form for $c_{-1} \neq 0$ is $z \frac{d}{dz} + \left( \begin{array}{cc} a_1 z & b \\ 1 & -a_1 z \end{array} \right) z^{a_1} + c_0$ with $b = b_{-1} z^{-1} + \cdots + b_2 z^2$ and equations

\begin{align*}
a_1^2 + b_2 c_0 &= 0, \\
a_1 + b_2 + b_1 c_0 &= 1, \\
b_{-1} &= t^2/4, \\
t^2/4 c_0 + b_0 &= t \theta/2.
\end{align*}

A standard form for $c_0 \neq 0$ is $z \frac{d}{dz} + \left( \begin{array}{cc} \frac{a_{-1}}{c_{-1}} z^{-1} & b \\ c_{-1} z^{-1} + 1 & -a_{-1} z^{-1} \end{array} \right) z^{a_{-1}} + c_1$ with equations

\begin{align*}
b_2 &= 0, \\
b_1 &= 1, \\
a_{-1}^2 + b_{-1} c_{-1} &= t^2/4, \\
b_{-1} + b_0 c_{-1} &= t \theta/2.
\end{align*}

By gluing the two standard forms, one obtains the nonsingular moduli space $\mathcal{M}(\theta)$. The map $\mathcal{M}(\theta) \to S(\alpha)$, where $\alpha = e^{i \theta}$, is a bijection.

**Observation.** After scaling some variables one sees that $\mathcal{M}(\theta)$ is the union of two open affine spaces $U_1 \times T$ and $U_2 \times T$, where $U_1$ is given by the variables $a_1, b_1, c_0$ and the relation $a_1^2 + (1 - a_1 - b_1 c_0) c_0 = 0$, and $U_2$ is given by the variables $a_{-1}, b_0, c_{-1}$ and the relation $a_{-1}^2 + (\frac{\theta}{2} - b_0 c_{-1}) c_{-1} - \frac{1}{4} = 0$.

Let $U_{12} \subset U_1$ be defined by $c_0 \neq 0$ and $U_{21} \subset U_2$ by $c_{-1} \neq 0$. The gluing of $U_1 \times T$ and $U_2 \times T$ is defined by the isomorphism $U_{12} \times T \to U_{21} \times T$ obtained by suitable base changes in the group $\{e_1 \mapsto e_1, e_2 \mapsto \alpha e_2 + (x_0 + z_1^2 e_1)\}$.

Using the two projections $U_1 \to \mathbb{C}, (a_1, b_1, c_0) \mapsto c_0$ and $U_2 \to \mathbb{C}, (a_{-1}, b_0, c_{-1}) \mapsto c_{-1}$ one finds that $U_1$ and $U_2$ are simply connected.

**Define** $M(\theta) := f^{-1}(1)$, where $f : \mathcal{M}(\theta) \to T$ is the canonical morphism. The space $M(\theta)$ is simply connected since it is the union of the two simply connected spaces $U_1, U_2$.

The universal covering of $\mathcal{M}(\theta)$ is $\tilde{M}(\theta) = \mathcal{M}(\theta) \times T$ and $\tilde{\mathcal{M}}(\theta)$ is the isomorphism $U_{12} \times T \to U_{21} \times T$ which is bijective (and thus an analytic isomorphism, see [3]). Indeed, $\mathcal{M}(\theta) \to S(\alpha)$ and $\tilde{\mathcal{M}}(\theta) \to \tilde{R}(\alpha) \times \tilde{T}$ are bijections.

**Theorem 2.2.** Let $\theta \in \mathbb{C}, \alpha = e^{i \theta}$. The extended Riemann–Hilbert map $\tilde{M}(\theta) \to \tilde{R}(\alpha) \times \tilde{T}$, with $\tilde{T} \cong \mathbb{C}$, is a well-defined analytic isomorphism.

**Comment.** The existence of an analytic isomorphism as in Theorem 2.2 is called the “geometric Painlevé property” in [1]. They prove this property for a number of Painlevé equations under a restriction on the parameters (loc. cit., Theorem 6.3). We prove it here for PIII(D6) and in Sections 3.3.2 and 3.4.4 below for PIII(D7) without any restriction.

### 2.3 Isomonodromy and the Okamoto-Painlevé space

The calculation is done on the ‘chart’ $c_0 \neq 0$ and $q$ is supposed to be invertible. The data for the operator $z \frac{d}{dz} + A$ are

\begin{align*}
c_{-1} &= -q, \\
b_{-1} &= q^{-1} \left( a_{-1}^2 - \frac{t^2}{4} \right), \\
b_0 &= -\frac{t \theta}{2} q^{-1} + q^{-2} \left( a_{-1}^2 - \frac{t^2}{4} \right), \\
b_1 &= 1, \\
b_2 &= 0.
\end{align*}

Now $q$ and $a_{-1}$ are functions of $t$ and the family is isomonodromic if there is an operator $\frac{d}{dt} + B$ commuting with $z \frac{d}{dz} + A$. Equivalently $A' = B + [A, B]$, where $'$ denotes $\frac{d}{dt}$ and $\circ$ denotes $z \frac{d}{dz}$.

The Lie algebra $\mathfrak{sl}_2$ has standard basis $H = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, $E_1 = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $E_2 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$. One writes $A = a_{-1} z^{-1} H + b E_1 + (-q z^{-1} + 1) E_2$ and $B = B_H H + B_1 E_1 + B_2 E_2$ with $B_* = \sum_{i=-1}^2 B_{*, i} z^i$.
for \( \ast = H, 1, 2 \) and \( B_{s, \ast} \) only depending on \( t \). Using the Lie algebra structure one obtains the equations:

\[
\begin{align*}
    a'_{-1}z^{-1} &= \bar{B}_H + B_2(z + b_0 + b_{-1}z^{-1}) - B_1(-qz^{-1} + 1), \\
    b'_0 + b'_{-1}z^{-1} &= \bar{B}_1 + 2B_1a_{-1}z^{-1} - 2B_H(z + b_0 + b_1z^{-1}), \\
    -q'z^{-1} &= \bar{B}_2 - 2B_2a_{-1}z^{-1} + 2B_H(-qz^{-1} + 1).
\end{align*}
\]

(E)\( H \)

(E)\( 1 \)

(E)\( 2 \)

By Maple one obtains the system

\[
q' = \frac{q + 2a_{-1}}{t}, \quad a'_{-1} = -\frac{t^2 - \theta tq + 4a_{-1}^2 + 2qa_{-1} + 2q^3}{2tq}
\]

and finally

\[
q'' = \left(\frac{q'}{q}\right)^2 - \frac{q'}{t} - \frac{\theta}{t} + \frac{2q^2}{t^2} - \frac{1}{q}.
\]

We note that the change \( q = -Q, t = -T \) brings this equation in the form

\[
\frac{Q''}{Q} = \frac{(Q')^2}{Q} - \frac{Q'}{T} - \frac{\theta}{T} - \frac{2Q^2}{T^2} - \frac{1}{Q} \quad \text{with notation} \quad \ast = \frac{d}{dT}.
\]

This is the standard form for \( \text{PIII}(D_7) \) (see [6]). As in [8, 9, 12] one obtains:

**Theorem 2.3.** The equation \( \text{PIII}(D_7) \) has the Painlevé property. The analytic fibration \( \tilde{\mathcal{M}}(\theta) \to \tilde{\mathcal{T}} = \mathbb{C} \) with its foliation \( \{\text{RH}^{-1}(r) \} \mid r \in \mathcal{R}(\alpha) \} \), where \( \text{RH} : \tilde{\mathcal{M}}(\theta) \to \mathcal{R}(\alpha) \) is the Riemann–Hilbert map, is isomorphic to the Okamoto–Painlevé space for the equation \( \text{PIII}(D_7) \) with parameter \( \theta \).

Moreover, \( \mathcal{M}(\theta) \cong \mathcal{R}(\alpha) \) is the space of initial values.

### 2.4 Automorphisms of \( S \) and Bäcklund transforms

The automorphism \( s_1 \) of \( S \) is defined by \( s_1(M, t) = (M, -t) \). The induced action on \( \mathcal{R} \) leaves all data invariant except for interchanging the basis vectors \( f_1, f_2 \) of \( V(0) \). As a consequence \( \alpha \) is mapped to \( -\alpha^{-1} \).

The automorphism \( s_2 \) of \( S \) is defined by \( s_2(M, t) = (N \otimes M, -t) \). Here \( N = \mathbb{C}(z)b \) is the differential module given by \( \delta(b) = \frac{1}{2}b \). Starting with a local presentation \( z^\frac{d}{dz} + \begin{pmatrix} \omega & 0 \\ 0 & -\omega \end{pmatrix} \) with \( \omega = \frac{t^2 - 1 + \theta}{2} \) of \( M \) at \( z = 0 \) one obtains, after conjugation with \( \begin{pmatrix} z & 0 \\ 0 & 1 \end{pmatrix} \), the local presentation \( z^\frac{d}{dz} + \begin{pmatrix} -\tau & 0 \\ 0 & \tau \end{pmatrix} \), with \( \tau = \frac{t^2 - 1 + \theta}{2} \), of \( N \otimes M \) at \( z = 0 \).

Starting with a local presentation \( D := z^\frac{d}{dz} + \begin{pmatrix} \frac{1}{4} & \frac{1}{4} \\ \frac{3}{4} & \frac{1}{4} \end{pmatrix} \) of \( M \) at \( z = \infty \) (say on the basis \( E_1, E_2 \), described in Section 2.1, part 2), one obtains the local presentation \( z^\frac{d}{dz} + \begin{pmatrix} \frac{1}{4} & \frac{1}{4} \\ \frac{3}{4} & \frac{1}{4} \end{pmatrix} \) of \( N \otimes M \) at \( z = \infty \). This is the matrix of \( D \) with respect to the basis \( zE_2, E_1 \). The induced action of \( s_2 \) on \( \mathcal{R} \) maps \( \alpha \) to \( -\alpha^{-1} \), the formal monodromy at \( \infty \) is multiplied by \( -1 \) and the Stokes data are essentially unchanged.

The group of automorphisms of \( S \), generated by \( s_1, s_2 \), has order 4. The Bäcklund transformations are the lifts of the elements of this group to isomorphisms (preserving isomonodromy) between various moduli spaces \( \mathcal{M}(\theta) \).
Geometric Aspects of the Painlevé Equations PIII(D₆) and PIII(D₇)

\[ s^+_1 : \hat{\mathcal{M}}(\theta) \to \hat{\mathcal{M}}(-\theta) \] is the obvious lift of \( s_1 \), given by \( \tilde{t} \mapsto \tilde{t} + \pi i \), \( \theta \mapsto -\theta \). Further any solution \( q(\tilde{t}) \) of PIII(D₇) for the parameter \( \theta \) is mapped to the solution \( q(\tilde{t} + \pi i) \) for the parameter \(-\theta\).

\[ s^+_2 : \hat{\mathcal{M}}(\theta) \to \hat{\mathcal{M}}(1 - \theta) \] is the obvious lift of \( s_2 \) with \( \tilde{t} \mapsto \tilde{t} + \pi i \). The formula for \( s^+_2 \) is not obvious and its computation is given below.

Put \( B := (s^+_2)^2 = (s^+_1)^2 \). Then \( B \) is the automorphism of \( \mathcal{M}(\theta) = M(\theta) \times \tilde{T} \), which is the identity on \( M(\theta) \) and \( B : \tilde{t} \mapsto \tilde{t} + 2\pi i \).

The group \( \langle s^+_1, s^+_2 \rangle \) generated by \( s^+_1 \), \( s^+_2 \) (for their action on \( \theta \), \( \tilde{t} \)) has \( \langle B \rangle \cong \mathbb{Z} \) as normal subgroup and \( \langle s^+_1, s^+_2 \rangle / \langle B \rangle \) is the affine Weyl group of type \( A_1 \).

**Computation of the Bäcklund transformation \( s^+_2 \):** A point \( \xi \in \mathcal{M}(\theta) \), lying in the affine open subset defined by \( c_0 \neq 0 \) and \( c_1 \neq 0 \), is represented by the operator in standard form

\[
\frac{dz}{dz} + \left( \begin{array}{cc}
\frac{a}{1 - qz^{-1}} & b \\
-\frac{a}{1 - qz^{-1}} & 0
\end{array} \right),
\]

where \( b = z - \frac{\theta}{2q} + \frac{a^2 - t^2}{q^2} + \frac{a^2 - t^2}{q^2} z^{-1} \). The map \( s^+_2 \) changes this operator into \( \frac{dz}{dz} + A \), where \( A \) is obtained from the above matrix by \( t \mapsto -t \) and adding

\[
\left( \begin{array}{cc}
\frac{1}{2} & 0 \\
0 & -\frac{1}{2}
\end{array} \right).
\]

The point \( s^+_2(\xi) \in \mathcal{M}(1 - \theta) \) is supposed to be represented by the operator \( \frac{dz}{dz} + \tilde{A} \), where \( \tilde{A} = \left( \begin{array}{cc}
\frac{\tilde{a} - t}{1 - \tilde{a}z^{-1}} & \tilde{b} \\
-\frac{\tilde{a} - t}{1 - \tilde{a}z^{-1}} & 0
\end{array} \right) \) with \( \tilde{b} = z - \frac{t(1 - \theta)}{2q} + \frac{\tilde{a}^2 - t^2}{q^2} + \frac{\tilde{a}^2 - t^2}{q^2} z^{-1} \). Since the two matrix differential operators represent the same irreducible differential module over \( \mathbb{C}(z) \), there is a \( T \in \text{GL}(2, \mathbb{C}(z)) \) not \( 0 \), unique up to multiplication by a constant, such that \( (\frac{dz}{dz} + A)(Tz^{-1} + \tilde{A}) \). A local computation shows that \( T \) has the form \( T_{-2} z^{-2} + T_{-1} z^{-1} + T_0 \neq 0 \) with constant matrices \( T \). The \( \tilde{a}, \tilde{q} \) and the entries of the \( T \) are the unknowns in the identity

\[
(z \frac{dz}{dz} + A)(T_{-2} z^{-2} + T_{-1} z^{-1} + T_0) = (T_{-2} z^{-2} + T_{-1} z^{-1} + T_0)(z \frac{dz}{dz} + \tilde{A}) \).
\]

A Maple computation yields

\[
\tilde{q} = -\frac{t(\theta q + 2a - t)}{2q^2}
\]

and

\[
\tilde{a} = \frac{t(4a^2 - 4at + 2aq + 2\theta a q + q^2 \theta + t^2 - tq \theta - qt - 2q^3)}{4q^3},
\]

The isomorphism \( s^+_2 \) respects the foliations. For a leaf one has \( q' = \frac{q + 2a}{t} \) and substitution in the first formula produces \( \tilde{q} = -\frac{t(\theta t + q - q - t)}{2q^2} \) for this Bäcklund transformation on solutions of PIII(D₇).

The Bäcklund transformation \( s^+_2 s^+_1 \) maps a solution \( q \) for the parameter \( \theta \) to the solution \( \frac{t(q - 2a - t)}{2q^2} \), with \( a = \frac{q - q}{2} \), with parameter \( 1 + \theta \).

### 2.5 Remarks

1. One considers for \( (M, t) \in \mathfrak{S} \) the connection \( (\nabla_0, \nabla) \) with generic fibre \( M \) and the local data

\[
\frac{dz}{dz} + \left( \begin{array}{cc}
\frac{1}{3} & \frac{z}{3} \\
1 & -\frac{1}{3}
\end{array} \right) \text{ at } z = \infty \text{ and } \frac{dz}{dz} + \left( \begin{array}{cc}
\omega & 0 \\
0 & -\omega
\end{array} \right) \text{ with } \omega = \frac{t z^{-1} + \theta}{2},
\]

at \( z = 0 \). The second exterior power of \( (\nabla_0, \nabla) \) is \( (O, d) \) and thus \( V_0 \) has degree 0. Since \( (\nabla_0, \nabla) \) is irreducible, there are two possibilities for \( V_0 \) namely \( O \oplus O \) and \( O(1) \oplus O(-1) \). Suppose that \( V_0 \cong O(1) \oplus O(-1) \). Then one can identify \( V_0 \) with \( O(\{\infty\}) e_1 + O(-\{\infty\}) e_2 \) and for a good choice of \( e_1, e_2 \) one obtains the operator \( \nabla_{\frac{dz}{dz}} = \frac{dz}{dz} + \left( \begin{array}{cc}
0 & b \\
z^{-1} & 0
\end{array} \right) \) with \( b = z^2 + \cdots \). One concludes that the locus of the modules \( M \) with \( V_0 = O(1) \oplus O(-1) \) is the set of the closed points of \( q^{-1}(\infty) \) for the map

\[
q := -\frac{2a}{c_1} : \mathcal{M}(\theta) \to \mathbb{P}^1 \text{ (see also Section 3.3.4).}
\]
2. Algebraic solutions of PIII(D\(_7\)). One easily finds the algebraic solution(s) \(q\) with \(q^3 = \frac{t^2}{2}\) for PIII(D\(_7\)) with \(\theta = 0\). Using the B"{a}cklund transformations one finds an algebraic solution for PIII(D\(_7\)) for every \(\theta \in \mathbb{Z}\). According to [5, 6], these are all the algebraic solutions of PIII(D\(_7\)).

More precisely, \(q_j(\tilde{t}) = e^{2\pi i j/3} e^{2i/3} \sqrt{2}\), \(j = 0, 1, 2\) are algebraic solution for \(\theta = 0\). We note that \(q_1(\tilde{t}) = q_0(\tilde{t} + 4\pi i)\) and \(q_2(\tilde{t}) = q_0(\tilde{t} + 2\pi i)\). Since \(\alpha = 1\) and top\(^3 = 1\), these solutions are mapped to a single point of \(\mathcal{R}(1)\) corresponding to \(c_1c_2 = -3\), \(e = -i\) and certain values for the invariants \(\ell_{12}, \ell_{14}, \ell_{23}, \ell_{34}\) (which we cannot make explicit). The isomonodromic family for this solution \(q\) is

\[
zh \frac{dz}{dz} + \begin{pmatrix} -\frac{q}{z} & -1 \\ -qz^{-1} & 1 \end{pmatrix} \quad \text{with} \quad b = z + \left( \frac{1}{36} - \frac{q}{2} \right) + q \left( \frac{1}{36} - \frac{q}{2} \right) z^{-1}
\]

and

\[
q^3 = \frac{t^2}{2}.
\]

It is not clear what makes this family and the corresponding point of \(\mathcal{R}(1)\) so special.

3. Special solutions of PIII(D\(_7\)). Consider an isomonodromy family for which the Stokes matrices are trivial, i.e., \(c_1 = c_2 = e = 0\). Then \(\alpha = i\) or \(\alpha = -i\). In the first case one computes that \(\ell_{12} = \ell_{14} = \frac{1}{3}, \ell_{23} = \ell_{34} = -\frac{1}{3}\) and one finds a unique point of \(\mathcal{R}(i)\) and a special solution \(q(\tilde{t})\) of PIII(D\(_7\)) for \(\theta = \frac{1}{2}\). Using B"{a}cklund transformations one obtains a similar special solution for any \(\theta \in \frac{1}{2} + \mathbb{Z}\). Y. Ohyama informed us that the condition \(c_1 = c_2 = 0\) implies that the corresponding solution \(q\) of PIII(D\(_7\)) is a univalent function of \(t\) and is meromorphic at \(t = 0\). Further \(\theta \in \frac{1}{2} + \mathbb{Z}\) is equivalent to \(e = 0\). See [2] for details.

3 The family \((1, -, 1)\)

3.1 Definition of the family

The set \(\mathcal{S}\) consists of the equivalence classes of pairs \((M, t)\), where \(M\) is a differential module \(M\) over \(\mathbb{C}(z)\) and \(t \in \mathbb{C}^*\) such that: dim \(M = 2\), \(\Lambda^2 M\) is the trivial module, \(M\) has two singularities \(0\) and \(\infty\), both singularities have Katz invariant 1, the (generalized) eigenvalues are normalized to \(\pm \frac{1}{2} z^{-1}\) at 0 and \(\pm \frac{1}{2} z\) at \(\infty\). Further, two pairs \((M_1, t_1)\) and \((M_2, t_2)\) are called equivalent if there exists an isomorphism \(M_1 \rightarrow M_2\) and \(t_1 = t_2\).

As in Section 2, we will have to replace \(T\) by its universal covering \(\tilde{T} = \mathbb{C} \rightarrow T, \tilde{t} \mapsto e^{\tilde{t}}\). Write \(\tilde{\mathcal{S}} = \mathcal{S} \times_T \tilde{T}\). Define for \(\alpha, \beta \in \mathbb{C}^*\) the subset \(\tilde{\mathcal{S}}(\alpha, \beta)\) of \(\tilde{\mathcal{S}}\) consisting of the pairs \((M, t)\) such that \(\mathbb{C}((z)) \otimes M\) is represented by \(zh \frac{dz}{dz} + \begin{pmatrix} \omega & 0 \\ 0 & -\omega \end{pmatrix}\) with \(\omega = \frac{t z^{-1} + \theta_0}{2}\), \(\alpha = e^{\pi i \theta_0}\) and \(\mathbb{C}((z^{-1})) \otimes M\) is represented by \(zh \frac{dz}{dz} + \begin{pmatrix} \tau & 0 \\ 0 & -\tau \end{pmatrix}\) with \(\tau = \frac{t z + \theta_\infty}{2}\), \(\beta = e^{\pi i \theta_\infty}\). Further \(\tilde{\mathcal{S}}(\alpha, \beta) = \mathcal{S}(\alpha, \beta) \times_T \tilde{T}\).

3.2 The monodromy space

For \((M, t) \in \mathcal{S}\), the monodromy data are given by (compare [10]): the symbolic solutions spaces \(V(0)\) and \(V(\infty)\) at \(z = 0\) and \(z = \infty\) (including formal monodromies and Stokes matrices) and the link \(L : V(0) \rightarrow V(\infty)\). We make this more explicit.

The module \(\mathbb{C}((z)) \otimes M\) has a basis \(E_1, E_2\) with \(\delta(E_1 \wedge E_2) = 0\) and \(\delta E_1 = -\frac{t z^{-1} + \theta_0}{2} E_1, \delta E_2 = \frac{t z^{-1} + \theta_0}{2} E_2\). We note that \(t\) is used to distinguish between \(E_1\) and \(E_2\). This basis is unique up to a transformation \(E_1 \mapsto c_1 z^m E_1, E_2 \mapsto c_2 z^{-m} E_2\) with \(c_1, c_2 \in \mathbb{C}^*, m \in \mathbb{Z}\). After fixing \(\theta_0\), the \(E_1, E_2\) are unique up to multiplication by constants. The symbolic solution space \(V(0)\) at \(z = 0\) is \(\mathbb{C} e_1 + \mathbb{C} e_2\), with \(e_1 = e^{-\frac{1}{2} z^{-1} + \frac{\theta_0}{2} \log z} E_1\) and \(e_2 = e^{\frac{1}{2} z^{-1} - \frac{\theta_0}{2} \log z} E_2\).
Now α = e^{πiθ} is well defined and does not depend on the choices for \( E_1, E_2 \).

Similarly, \( \mathbb{C}(z^{-1}) \otimes M = \mathbb{C}(z^{-1})F_1 \oplus \mathbb{C}(z^{-1})F_2 \) with \( \delta(F_1 \wedge F_2) = 0 \), \( \delta F_1 = \frac{-iz + \theta \pi}{2} F_1 \) and \( \delta F_2 = \frac{iz + \theta \pi}{2} F_2 \). The space \( V(\infty) \) has basis \( f_1 = e^{\frac{iz}{2} + \theta \pi \log z} F_1 \) and \( f_2 = e^{-\frac{iz}{2} - \theta \pi \log z} F_2 \) over \( \mathbb{C} \). Moreover, \( \beta = e^{πiθ} \).

For the basis \( e_1, e_2 \) of \( V(0) \), the formal monodromy and the Stokes matrices are:

\[
\begin{pmatrix}
\alpha & 0 \\
0 & \frac{1}{\alpha}
\end{pmatrix},
\begin{pmatrix}
1 & 0 \\
a_1 & 1
\end{pmatrix},
\begin{pmatrix}
1 & a_2 \\
0 & 1
\end{pmatrix}
\]

with product

\[
\begin{pmatrix}
\alpha & 0 \\
0 & \frac{1}{\alpha}
\end{pmatrix},
\begin{pmatrix}
\frac{a_1}{\alpha} & 0 \\
0 & \frac{1+a_1a_2}{\alpha}
\end{pmatrix}.
\]

This product is the topological monodromy top_{0\alpha} at \( z = 0 \).

For the basis \( f_1, f_2 \) of \( V(\infty) \), the formal monodromy and the Stokes matrices are:

\[
\begin{pmatrix}
\beta & 0 \\
0 & \frac{1}{\beta}
\end{pmatrix},
\begin{pmatrix}
1 & 0 \\
b_1 & 1
\end{pmatrix},
\begin{pmatrix}
1 & b_2 \\
0 & 1
\end{pmatrix}
\]

with product

\[
\begin{pmatrix}
\beta & 0 \\
0 & \frac{1}{\beta}
\end{pmatrix},
\begin{pmatrix}
\frac{b_1}{\beta} & 0 \\
0 & \frac{1+b_1b_2}{\beta}
\end{pmatrix}.
\]

This is the topological monodromy \( \text{top}_\infty \) at \( z = \infty \).

The link \( L : V(0) \to V(\infty) \) with matrix \( \begin{pmatrix} \ell_1 & \ell_2 \\ \ell_3 & \ell_4 \end{pmatrix} \) has determinant 1.

The relations are given by the matrix equality

\[
\begin{pmatrix}
\frac{b_2}{\beta} \\
\beta
\end{pmatrix} \begin{pmatrix}
\frac{b_2}{\beta} \\
1 + \beta b_2
\end{pmatrix} = L \circ \begin{pmatrix}
\alpha & \frac{a_1a_2}{\alpha} \\
\frac{a_1}{\alpha} & \frac{1+a_1a_2}{\alpha}
\end{pmatrix} \circ L^{-1}.
\]

In particular, \( \beta = \ell_1\ell_4\alpha + \ell_2\ell_4\frac{a_1}{\alpha} - \ell_1\ell_3\alpha a_2 - \ell_2\ell_3\frac{1+a_1a_2}{\alpha} \). This defines a variety \( \mathcal{T} \), given by the variables \( \alpha, a_1, a_2, \ell_1, \ldots, \ell_4 \) with the only restrictions \( \ell_1\ell_4 - \ell_2\ell_3 = 1, \alpha \neq 0 \) and \( \ell_1\ell_4\alpha + \ell_2\ell_4\frac{a_1}{\alpha} - \ell_1\ell_3\alpha a_2 - \ell_2\ell_3\frac{1+a_1a_2}{\alpha} \neq 0 \).

For fixed values of \( \alpha, \beta \in \mathbb{C}^* \) we obtain a variety \( \mathcal{T}(\alpha, \beta) \) defined by the variables \( a_1, a_2, \ell_1, \ldots, \ell_4 \) and the relations:

\[
\ell_1\ell_4 - \ell_2\ell_3 = 1 \quad \text{and} \quad \beta = \ell_1\ell_4\alpha + \ell_2\ell_4\frac{a_1}{\alpha} - \ell_1\ell_3\alpha a_2 - \ell_2\ell_3\frac{1+a_1a_2}{\alpha}.
\]

The group \( \mathbb{G}_m \times \mathbb{G}_m \) acts on \( \mathcal{T} \) and \( \mathcal{T}(\alpha, \beta) \), by base change \( (e_1, e_2, f_1, f_2) \mapsto (\gamma e_1, \gamma^{-1} e_2, \delta f_1, \delta^{-1} f_2) \). The categorical quotient of \( \mathcal{T} \) by \( \mathbb{G}_m \times \mathbb{G}_m \) is \( \mathcal{R} \to \mathcal{P} \) with parameter space \( \mathcal{P} = \mathbb{C}^* \times \mathbb{C}^* \) given by \( (\alpha, \beta) \). This is a family of affine cubic surfaces \( \mathcal{R}(\alpha, \beta) \) (this is the categorical quotient of \( \mathcal{T}(\alpha, \beta) \)) given by the equation

\[
x_1 x_2 x_3 + x_1^2 + x_2^2 + (1 + \alpha \beta)x_1 + (\alpha + \beta)x_2 + \alpha \beta = 0,
\]

where

\[
x_1 = \ell_1\ell_4 - 1, \quad x_2 = \alpha a_2\ell_1\ell_3 - \alpha \ell_1\ell_4, \quad x_3 = \frac{1+a_1a_2}{\alpha} + \alpha.
\]

**Observation:** \( \mathcal{R}(\alpha, \beta) \) is simply connected if \( \alpha \neq \beta \pm 1 \).

Define \( U \) by removing the two lines \{ \((0, -\beta, *)\), \((-1, 0, *)\) \} from \( \mathcal{R}(\alpha, \beta) \). The image of the projection \( (x_1, x_2, x_3) \in U \mapsto (x_1, x_2) \in \mathbb{C}^2 \) is \( \mathbb{C}^* \times \mathbb{C}^* \cup \{ (0, -\alpha), (-\alpha, 0) \} \). This image is simply connected. For \( x_1 x_2 \neq 0 \), the fiber is one point. For \( x_1 x_2 = 0 \), the fiber is an affine line. It follows that \( U \) is simply connected and thus \( \mathcal{R}(\alpha, \beta) \) is simply connected, too.

**Definition of the link and the topological monodromies.** A construction similar to the one in Section 2 is needed for the definition of the link. For \( \tilde{t} = |t| e^{iφ} \in \tilde{\mathbb{T}}, \phi \in \mathbb{R} \) the singular directions at \( z = 0 \) and \( z = \infty \) are \( \phi, \phi - π \) and \( -\phi, \pi - \phi \). On the universal covering of \( \mathbb{P}^1 \setminus \{0, \infty\} \) one considers the path \( \tilde{z} = re^{i\phi(t)} \), \( 0 < r < \infty \) with \( d(r) = \frac{1}{1+r}(\phi - \frac{π}{2}) + \frac{r}{1+r}(\frac{π}{2} - \phi) \). The link \( L : V(0) \to V(\infty) \) is defined by (multi)summation at zero in the direction \( \phi - \frac{π}{2} \), followed by
analytic continuation along the above path and finally the inverse of (multi)summation in the
direction $\frac{d}{dz} - \phi$ at infinity. Now the map $S(\alpha, \beta) \to R(\alpha, \beta) \times T$ is well defined.

In the general case, i.e., $\alpha \neq \beta^{\pm 1}$, the space $R(\alpha, \beta)$ is the geometric quotient of $T(\alpha, \beta)$ and this space is nonsingular. Therefore the natural map $S(\alpha, \beta) \to R(\alpha, \beta) \times T$ is a bijection.

Let $(M, t) \in S(\alpha, \beta)$. Then $M$ is reducible if and only if its monodromy data (in $R(\alpha, \beta)$) is reducible. Further $R(\alpha, \beta)$ contains reducible monodromy data if and only if $\alpha = \beta^{\pm 1}$. Thus $S(\alpha, \beta)$ contains reducible modules if and only if $\alpha = \beta^{\pm 1}$. We will first investigate the general case $\alpha \neq \beta^{\pm 1}$. The special case $\alpha = \beta^{\pm 1}$ presents many difficulties and will be handled later on.

### 3.3 The general case $\alpha \neq \beta^{\pm 1}$

#### 3.3.1 The moduli space $M(\theta_0, \theta_\infty)$

Fix $\theta_0, \theta_\infty$ with $\alpha = e^{i\pi \theta_0}, \beta = e^{i\pi \theta_\infty}$. We will construct a moduli space $M(\theta_0, \theta_\infty)$ of connections on the bundle $Oe_1 \oplus O(-[0])e_2$ on $\mathbb{P}^1$ such that the map, which associates to a connection in this space its generic fiber, is a bijection $M(\theta_0, \theta_\infty) \to S(\alpha, \beta)$.

The elements of the set $M(\theta_0, \theta_\infty)$ are the connections $\nabla : V \to \Omega(2[0] + 2[\infty]) \otimes V$ defined by: the generic fiber $M$ satisfies $(M, t) \in S(\alpha, \beta)$; the invariant lattices at $z = 0$ and $z = \infty$ are given by the local matrix differential operators $z \frac{d}{dz} + \begin{pmatrix} a & b \\ c & -a \end{pmatrix}$ with $a = a_{-1}z^{-1} + a_0 + a_1z, b = b_{-2}z^{-2} + \cdots + b_1z, c = c_0 + c_1z$. The lattice condition at $z = 0$ is equivalent to $a(a - 1) + bc \in (\frac{z^{-1} + \theta_0}{2})^2 - (\frac{z^{-1} + \theta_0}{2}) + \mathbb{C}[z]$. This leads to the equations

$$a_{-2}^2 + b_{-2}c_0 = \frac{t^2}{4}, \quad 2a_{-1}a_0 - a_{-1} + b_{-2}c_1 + b_{-1}c_0 = t \left( \frac{\theta_0}{2} - \frac{1}{2} \right).$$

The lattice condition at $z = \infty$ is equivalent to $a^2 + bc \in (\frac{z + \theta_\infty}{2})^2 + \mathbb{C}[[z^{-1}]]$ and one finds the equations

$$a_1^2 + b_1c_1 = \frac{t^2}{4}, \quad 2a_0a_1 + b_0c_1 + b_1c_0 = \frac{t\theta_\infty}{2}.$$

Define the (quasi-)affine space $A(\theta_0, \theta_\infty)$ by the variables $a_*, b_*, c_*, t$, the four equations and the open condition $(c_0, c_1) \neq (0, 0)$. For the general case $\alpha \neq \beta^{\pm 1}$, the module $M$ and the corresponding connection are irreducible and thus $(c_0, c_1) \neq (0, 0)$ holds (see Remarks 3.2.3).

The space $A(\theta_0, \theta_\infty)$ is divided out by the group of the automorphisms of the bundle $Oe_1 \oplus O(-[0])e_2$. This action amounts to dividing $A(\theta_0, \theta_\infty)$ by the group $G$ of transformations $e_1 \mapsto \lambda e_1, e_2 \mapsto \lambda e_2 + (\gamma z^{-1} + \delta)e_1$.

**Proposition 3.1.** The quotient of $A(\theta_0, \theta_\infty)$ by $G$ is geometric and has no singularities.

**Proof.** The open subset $A(\theta_0, \theta_\infty)_1$, defined by $c_1 \neq 0$, contains the closed ‘standard subset’ $S\mathcal{T}_1$, given by the connections

$$z \frac{d}{dz} + \begin{pmatrix} a_{-1}z^{-1} & b \\ z + c_0 & -a_{-1}z^{-1} \end{pmatrix} \quad \text{with} \quad b = b_{-2}z^{-2} + \cdots + b_1z,$$

$$b_1 = \frac{t^2}{4}, \quad b_0 = -\frac{t^2}{4} c_0 + \frac{t \theta_\infty}{2}, \quad b_{-2} = a_{-1} - b_{-1}c_0 + t \left( \frac{\theta_0}{2} - \frac{1}{2} \right).$$
and the equation
\[ a_1^2 + c_0 \left( a_{-1} - b_{-1}c_0 + t \left( \frac{\theta_0}{2} - \frac{1}{2} \right) \right) - \frac{t^2}{4} = 0. \]

The natural morphism \( G \times ST_1 \to M(\theta_0, \theta_\infty) \) is an isomorphism.

Similarly, let \( ST_0 \) denote the closed subset of the open subset \( A(\theta_0, \theta_\infty) \), defined by \( c_0 \neq 0 \), be given by the connections
\[
\begin{align*}
  &z \frac{d}{dz} + \left( \frac{a_1}{c_1z + 1} - a_1z \right) \quad \text{with} \quad b = b_{-2}z^{-2} + \cdots + b_1z, \\
  &b_{-2} = \frac{t^2}{4}, \quad b_{-1} = t \left( \frac{\theta_0}{2} - \frac{1}{2} \right) - \frac{t^2}{4}c_1, \quad b_1 = \frac{t\theta_\infty}{2} - b_0c_1
\end{align*}
\]
and the equation
\[ a_1^2 + \left( \frac{t\theta_\infty}{2} - b_0c_1 \right) c_1 - \frac{t^2}{4} = 0. \]

Again \( G \times ST_0 \to A(\theta_0, \theta_\infty) \) is an isomorphism. The quotient of \( A(\theta_0, \theta_\infty) \) by \( G \) is obtained by gluing the two non-singular spaces \( ST_1 \) and \( ST_0 \).

Now \( M(\theta_0, \theta_\infty) \) is, as an algebraic variety, defined as the quotient of \( A(\theta_0, \theta_\infty) \) by \( G \). Since this is a geometric quotient, the map \( M(\theta_0, \theta_\infty)(\mathbb{C}) \to S(\alpha, \beta) \) is bijective.

**Remarks 3.2.**
1. As in Section 2, the Observation, one sees that, after scaling some of the variables, the two charts \( ST_1, \; ST_0 \) of \( M(\theta_0, \theta_\infty) \), have the form \( U_1 \times T, \; U_2 \times T \) with simply connected spaces \( U_1, \; U_2 \).

Define \( M(\theta_0, \theta_\infty) = f^{-1}(1) \), where \( f : M(\theta_0, \theta_\infty) \to T \) is the canonical morphism. Then \( M(\theta_0, \theta_\infty) \) is simply connected.

Further, \( \tilde{M}(\theta_0, \theta_\infty) := M(\theta_0, \theta_\infty) \times_T \tilde{T} \) is the universal covering of \( M(\theta_0, \theta_\infty) \).

2. Let \( q : M(\theta_0, \theta_\infty) \to \mathbb{P}^1 \) denote the morphism given by \( q = -\frac{c_0}{c_1} \).

3. In the cases \( \alpha = \beta \pm 1 \), the space \( A(\theta_0, \theta_\infty) \) is defined as before, and including the assumption \( (c_0, c_1) \neq (0, 0) \). The space \( M(\theta_0, \theta_\infty) \) is again the geometric and non-singular quotient of \( A(\theta_0, \theta_\infty) \) by \( G \). The canonical map \( M(\theta_0, \theta_\infty)(\mathbb{C}) \to S(\alpha, \beta) \) is injective and, in general, not surjective.

Indeed, the open condition \( (c_0, c_1) \neq (0, 0) \) is valid for \( (M, t) \in S(\alpha, \beta) \) such that \( M \) is irreducible but may exclude certain reducible modules in \( S(\alpha, \beta) \). We note that \( c_0 = c_1 = 0 \) implies \( \pm \frac{\theta_\infty}{2} = \frac{\theta_0}{2} - \epsilon \) with \( \epsilon \in \{0, 1\} \).

### 3.3.2 The Okamoto–Painlevé space \( \tilde{M}(\theta_0, \theta_\infty) \) for \( \frac{\theta_0}{2} \pm \frac{\theta_\infty}{2} \notin \mathbb{Z} \)

The moduli space \( M(\theta_0, \theta_\infty) \) is replaced by \( \tilde{M}(\theta_0, \theta_\infty) := M(\theta_0, \theta_\infty) \times_T \tilde{T} \). The bijections \( \tilde{S}(\alpha, \beta) \to R(\alpha, \beta) \times \tilde{T} \) and \( \tilde{M}(\theta_0, \theta_\infty) \to \tilde{S}(\alpha, \beta) \) imply that the analytic morphism \( \tilde{M}(\theta_0, \theta_\infty) \to R(\alpha, \beta) \times \tilde{T} \) is bijective and hence an analytic isomorphism. As in Theorem 2.3, using arguments presented in [8, 9, 12] this implies the following result.

**Theorem 3.3.** Suppose that \( \frac{\theta_0}{2} \pm \frac{\theta_\infty}{2} \notin \mathbb{Z} \) (equivalently \( \alpha \neq \beta \pm 1 \)). Then \( \tilde{M}(\theta_0, \theta_\infty) \to \tilde{T} \), provided with the foliation given by the fibers of \( \tilde{M}(\theta_0, \theta_\infty) \to R(\alpha, \beta) \) (i.e., the isomonodromy families), is the Okamoto–Painlevé space corresponding to the equation \( \text{PIII}(D_6) \), namely

\[ q'' = \frac{(q')^2}{q} - \frac{q'}{t} - 4(\theta_0 - 1) + \frac{4\theta_\infty q^2}{t} + 4q^3 - \frac{4}{q}. \]

Moreover, this equation satisfies the Painlevé property.
Observations 3.4. 1. The above formula differs slightly from the one given in [10, Section 4.5]. This is due to different choices of the standard matrix differential operator.

2. The transformation \( t \mapsto -t, \theta_{\infty} \mapsto -\theta_{\infty} \) and \( \theta_0 \mapsto -\theta_0 + 2 \) leaves the family of matrix differential operators invariant. This has the consequence that a solution \( q(t) \) of PIII(D_6) with parameters \( \theta_0 \) and \( \theta_{\infty} \), yields the solution \( q(-t) \) of PIII(D_6) with parameters \(-\theta_0 + 2 \) and \(-\theta_{\infty} \). This can also be seen directly from the differential equation.

3. The solutions \( q(t) \) of PIII(D_6) are in fact meromorphic functions in \( \tilde{t} \in \tilde{T} = \mathbb{C} \). Thus \( Q(\tilde{t}) := q(e^{\tilde{t}}) \) is well defined and satisfies the equation

\[
Q'' = \frac{(Q')^2}{Q} - 4(\theta_0 - 1)e^{\tilde{t}} + 4\theta_{\infty}Q^2e^{\tilde{t}} + 4Q^3e^{2\tilde{t}} - \frac{4e^{2\tilde{t}}}{Q},
\]

where \( \tilde{t} = \frac{d}{dt} \).

4. The space of initial conditions is analytically isomorphic to \( R(\alpha, \beta) \) and can also be identified with \( M(\theta_0, \theta_{\infty}) \). Indeed, the extended Riemann–Hilbert isomorphism \( \mathcal{M}(\theta_0, \theta_{\infty}) \rightarrow R(\alpha, \beta) \times \tilde{T} \) induces an analytic isomorphism \( M(\theta_0, \theta_{\infty}) \rightarrow R(\alpha, \beta) \).

### 3.3.3 Verification of the formula in Theorem 2.3

On the chart \( ST_1 \) of \( M(\theta_0, \theta_{\infty}) \) the matrix differential operator has the form \( z \frac{d}{dz} + A = z \frac{d}{dz} + a_{-1}z^{-1}H + bE_1 + (z - q)E_2 \), where \( H = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \), \( E_1 = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \), \( E_2 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \). We will use \( [H, E_1] = 2E_2 \), \( [H, E_2] = -2E_2 \), \( [E_1, E_2] = H \). Further

\[
q := -c_0, b = b_{-2}z^{-2} + b_{-1}z^{-1} + b_0 + b_1z,
\]

where \( b_{-2} \neq 0 \) (by assumption),

\[
b_1 = \frac{t^2}{4}, \quad b_0 = \frac{t^2}{4} + \frac{t\theta_{\infty}}{2}, \quad b_{-2} = a_{-1} + qb_{-1} + t\left(\frac{\theta_0}{2} - \frac{1}{2}\right),
\]

\[
a^2_{-1} - q \left(a_{-1} + qb_{-1} + t\left(\frac{\theta_0}{2} - \frac{1}{2}\right)\right) - \frac{t^2}{4} = 0.
\]

Now \( q, a_{-1} \) are considered as (meromorphic) functions of \( t \) and \( A \) is a matrix depending on \( z \) and \( t \). The family \( z \frac{d}{dz} + A \) is isomonodromic if and only if there is an operator of the form \( \frac{d}{dt} + B = Z \frac{d}{dz} + B_{H}H + B_{E_1}E_1 + B_{E_2}E_2 \) which commutes with \( z \frac{d}{dz} + A \). This is equivalent to \( \frac{d}{dt}(A) = z \frac{d}{dz}B + [B, A] \).

Further \( B_{s} = B_{H}, B_{1}, B_{2} \) are functions of \( t, z \) and are supposed to have the form \( B_{s-2}(z^{-2} + B_{s-1}(z^{-1} + B_{s,0}(t) + B_{s,1}(t))z) \). The two operators commute if and only if \( a_{-1}z^{-1}H + b' E_1 - q'E_2 \) is equal to

\[
\tilde{X} = \tilde{B}_{H}H + \tilde{B}_{E_1}E_1 + \tilde{B}_{E_2}E_2 - [\tilde{B}_{H}H + \tilde{B}_{E_1}E_1 + \tilde{B}_{E_2}E_2, a_{-1}z^{-1}H + bE_1 + (z - q)E_2],
\]

where \( \tilde{X} \) stands for \( z \frac{d}{dz}(X) \) and \( X' := \frac{d}{dt}(X) \). On obtains the equations

\[
(H) \quad a'_{-1}z^{-1} = \tilde{B}_{H}H - B_{1}(z - q) + B_{2}b,
\]

\[
(E_1) \quad b' = \tilde{B}_{1} - 2B_{H}b + 2B_{1}a_{-1}z^{-1},
\]

\[
(E_2) \quad -q' = \tilde{B}_{2} + 2B_{H}(z - q) - 2B_{2}a_{-1}z^{-1}.
\]

A Maple computation shows that this system of differential equations for \( q, a_{-1} \) is equivalent to

\[
q' = \frac{4a_{-1} - q}{t}, \quad a'_{-1} = \frac{4a_{-1}^2 - t^2 + q(t - a_{-1} - t\theta_0) + q^2t\theta_{\infty} + q^4t^2}{tq}.
\]
The equation

\[ q'' = \frac{(q')^2}{q} - \frac{q'}{t} - \frac{4(\theta_0 - 1)}{t} + \frac{4\theta_\infty q^2}{t} + 4q^3 - \frac{4}{q} \]

follows by substitution. Using the transformation \( z \mapsto z^{-1} \) one finds that \( Q = \frac{1}{q} \) satisfies the PIII\((D_6)\) equation with \( \theta_0 - 1 \) and \( \theta_\infty \) interchanged:

\[ Q'' = \frac{(Q')^2}{Q} - \frac{Q'}{t} - \frac{4\theta_\infty}{t} + \frac{4(\theta_0 - 1)Q^2}{t} + 4Q^3 - \frac{4}{Q}. \]

### 3.3.4 After a remark by Yousuke Ohyama

Let \((M, t) \in \mathbf{S}(\alpha, \beta)\) with \( \alpha = e^{\pi i \theta_0}, \beta = e^{\pi i \theta_\infty} \) have the property that \( M \) is irreducible. Consider the connection \((\mathcal{W}, \nabla)\) with generic fiber \( M \) and locally represented by

\[ z \frac{d}{dz} + \left( \frac{tz + \theta_2}{2} - \frac{tz - \theta_0}{2} \right) \text{ at } z = 0 \quad \text{ and } \quad z \frac{d}{dz} + \left( \frac{tz - \theta_\infty}{2} - \frac{tz + \theta_\infty}{2} \right) \text{ at } z = \infty. \]

The second exterior product of \((\mathcal{W}, \nabla)\) is trivial and thus \( \Lambda^2 \mathcal{W} \) has degree 0. Since \( M \) is irreducible one has \( \mathcal{W} \cong O(k) \oplus O(-k) \) with \( k \in \{0, 1\} \).

Suppose that the connection \( \mathcal{W} \) has type \( O(1) \oplus O(-1) \). Then we can identify \( \mathcal{W} \) with \( O([0])B_1 \oplus O([-1])B_2 \). Put \( D := \nabla z^2 t \). Now \( DB_1 \) is not a multiple of \( B_1 \) since \( M \) is irreducible. After multiplying \( B_1 \) with a scalar, the matrix of \( D \) with respect to the basis \( B_1, B_2 \) has the form \( \begin{pmatrix} \alpha & \beta \\ z & -\alpha \end{pmatrix} \) with \( \alpha = \alpha_{-1}z^{-1} + \alpha_0 + \alpha_1z, \beta = \beta_{-3}z^{-3} + \cdots + \beta_1z \). The base vector \( B_2 \) can be replaced by \( B_2 + hB_1 \) with \( h = h_0 + h_{-1}z^{-1} + h_{-2}z^{-2} \). The result is a new representation of \( D \), namely

\[ \begin{pmatrix} 1 & h \\ 0 & 1 \end{pmatrix}^{-1} \left\{ z \frac{d}{dz} + \begin{pmatrix} \alpha & \beta \\ z & -\alpha \end{pmatrix} \right\} \begin{pmatrix} 1 & h \\ 0 & 1 \end{pmatrix} = z \frac{d}{dz} + \left( \frac{\alpha - hz}{z} \frac{2a h - h^2 z + \frac{d h}{dz}}{-\alpha + h z} + \beta \right). \]

For unique \( h_0, h_{-1} \) and at most two values of \( h_{-2} \), the last operator is

\[ z \frac{d}{dz} + \left( \frac{a_{-1}z^{-1}b}{z - a_{-1}z^{-1}} \right), \quad \text{ where } \quad b = b_{-2}z^{-2} + b_{-1}z^{-1} + b_0 + b_1z. \]

Let \( e_1, e_2 \) denote the new basis. Then \( \mathcal{V} = Oe_1 \oplus O([-1])e_2 \) and the corresponding point \( \xi \in \mathcal{M}(\theta_0, \theta_\infty) \) satisfies \( q(\xi) = 0 \). The converse holds, too. One observes that \( q^{-1}(0) \subset \mathcal{M}(\theta_0, \theta_\infty) \) has two connected components, each one isomorphic to \( \mathbb{A}^1 \times T \). We note that the map \( Q := \frac{1}{q} \) can also be used in this context, since for a monodromic family \( Q \) satisfies a PIII\((D_6)\) equation (see the end of Section 3.3.3).

According to Malgrange, the locus where the bundle \( \mathcal{W} \) is not free is the tau-divisor. Thus we find that the tau-divisor coincides with the locus \( Q^{-1}(\infty) \subset \mathcal{M}(\theta_0, \theta_\infty) \). The statement: ‘the tau-divisor coincides with \( q^{-1}(\infty) \)’ holds for PI, PII, PIII\((D_7)\), PIII\((D_8)\), PIV, too (see [8, 9, 12]).

### 3.4 The cases \( \alpha = \beta \pm 1 \)

#### 3.4.1 Geometric quotients of the monodromy data

We use here the notation of Section 3.2.

1. If \( \alpha = \beta \neq \pm 1 \), then \( \mathcal{R}(\alpha, \alpha) \) has a singular point, namely \((x_1, x_2, x_3) = (0, -\alpha, \alpha + \alpha^{-1})\). The preimage in \( \mathcal{T}(\alpha, \alpha) \) of this singular point consists of the tuples \((a_1, a_2, \ell_1, \ldots, \ell_4)\) such that
the matrices $L$, top$_0$ have the form \[
\begin{pmatrix}
\ell_1 0 \\
\ell_3 0
\end{pmatrix}
\begin{pmatrix}
\alpha \\
0
\end{pmatrix}
\begin{pmatrix}
0 \\
\ell_4
\end{pmatrix}
\begin{pmatrix}
\alpha / \alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
1 / \alpha
\end{pmatrix}
\begin{pmatrix}
\ell_2 0 \\
\ell_4 0
\end{pmatrix}
\begin{pmatrix}
\alpha \\
0
\end{pmatrix}
\begin{pmatrix}
a_2 \\
\alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
\ell_4
\end{pmatrix}
\begin{pmatrix}
\alpha / \alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
1 / \alpha
\end{pmatrix}
.\]
In particular, $\mathcal{R}(\alpha, \alpha)$ is not a geometric quotient.

The remedy consists of replacing $\mathcal{T}(\alpha, \alpha)$ by $\mathcal{T}(\alpha, \alpha)^*$ which is the complement of the closed subset of $\mathcal{T}(\alpha, \alpha)$ given by the equations $\ell_2 = \ell_3 = a_1 = a_2 = 0$. We claim that $\mathcal{T}(\alpha, \alpha)^*$ has a nonsingular geometric quotient by the action of $\mathbb{G}_m \times \mathbb{G}_m$. A proof is obtained by writing $\mathcal{T}(\alpha, \alpha)^*$ as the union of the four affine open subsets $\ell_2 \neq 0$, $\ell_3 \neq 0$, $a_1 \neq 0$ and $a_2 \neq 0$. On each of these subsets one explicitly computes the quotient by $\mathbb{G}_m \times \mathbb{G}_m$, which turns out to be nonsingular and geometric. Gluing these four quotients produces the required geometric quotient which will be denoted by $\mathcal{R}(\alpha, \alpha)^*$.

Let $\mathcal{S}(\alpha, \alpha)^*$ the complement in $\mathcal{S}(\alpha, \alpha)$ of the set of the modules which are direct sums and $\mathcal{S}(\alpha, \alpha)^* = \mathcal{S}(\alpha, \alpha)^* \times_T \hat{T}$. Then the canonical map $\tilde{\mathcal{S}}(\alpha, \alpha)^* \to \mathcal{R}(\alpha, \alpha)^* \times \hat{T}$ is bijective.

Define the closed space $\mathcal{T}(\alpha, \alpha)^*_{\text{red}}$ of $\mathcal{T}(\alpha, \alpha)^*$ by the condition that the data is reducible. This space has two irreducible components, given in terms of the matrices $L$, top$_0$ by:

(a) \[
\begin{pmatrix}
\ell_1 0 \\
\ell_3 0
\end{pmatrix}
\begin{pmatrix}
\alpha \\
0
\end{pmatrix}
\begin{pmatrix}
0 \\
\ell_4
\end{pmatrix}
\begin{pmatrix}
\alpha / \alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
1 / \alpha
\end{pmatrix}
\begin{pmatrix}
\ell_2 0 \\
\ell_4 0
\end{pmatrix}
\begin{pmatrix}
\alpha \\
0
\end{pmatrix}
\begin{pmatrix}
a_2 \\
\alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
\ell_4
\end{pmatrix}
\begin{pmatrix}
\alpha / \alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
1 / \alpha
\end{pmatrix}
.\]
with $\ell_1 \ell_4 = 1$ and $(\ell_3, a_1) \neq 0$. One easily verifies that the map which sends $(L, \text{top}_0)$ to $(\ell_3 : a_1) \in \mathbb{P}^1$ is the geometric quotient.

(b) \[
\begin{pmatrix}
\ell_1 0 \\
0
\end{pmatrix}
\begin{pmatrix}
\alpha \\
0
\end{pmatrix}
\begin{pmatrix}
0 \\
\ell_4
\end{pmatrix}
\begin{pmatrix}
\alpha / \alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
1 / \alpha
\end{pmatrix}
\begin{pmatrix}
\ell_2 0 \\
0
\end{pmatrix}
\begin{pmatrix}
\alpha \\
0
\end{pmatrix}
\begin{pmatrix}
a_2 \\
\alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
\ell_4
\end{pmatrix}
\begin{pmatrix}
\alpha / \alpha
\end{pmatrix}
\begin{pmatrix}
0 \\
1 / \alpha
\end{pmatrix}
.\]
with $\ell_1 \ell_4 = 1$ and $(\ell_2, a_2) \neq 0$. One easily verifies that the map which sends the $(L, \text{top}_0)$ to $(\ell_2 : a_2) \in \mathbb{P}^1$ is the geometric quotient.

Therefore the ‘reducible locus’ $\mathcal{R}(\alpha, \alpha)^*_{\text{red}}$ (i.e., corresponding to reducible monodromy data) is the union of two, not intersecting, projective lines.

2. The case $\alpha = \beta^{-1} \neq \pm 1$ can be handled as in (1). One finds (with a similar notation) a geometric quotient $\mathcal{R}(\alpha, \alpha^{-1})^*$ of $\mathcal{T}(\alpha, \alpha^{-1})^*$ and a bijection $\tilde{\mathcal{S}}(\alpha, \alpha^{-1})^* \to \mathcal{R}(\alpha, \alpha^{-1})^* \times \hat{T}$. Further $\mathcal{R}(\alpha, \alpha^{-1})^*_{\text{red}}$ is the union of two, non intersecting, projective lines.

3. $\alpha = \beta = 1$. The categorical quotient $\mathcal{R}(1,1)$ of $\mathcal{T}(1,1)$ has two singular points, namely $(x_1, x_2, x_3) = (0, -1, 2)$ and $(x_1, x_2, x_3) = (-1, 0, 2)$. The preimage of the first singular point consists of the pairs $(L, \text{top}_0)$ equal to \[
\begin{pmatrix}
\ell_1 & \ell_2 \\
0 & \ell_4
\end{pmatrix}
\begin{pmatrix}
1 & a_2 \\
0 & 1
\end{pmatrix}
\] or to \[
\begin{pmatrix}
\ell_1 & \ell_2 \\
0 & \ell_4
\end{pmatrix}
\begin{pmatrix}
a_2 \\
1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix}
.\]
The preimage of the second singular point consists of the pairs $(L, \text{top}_0)$ equal to \[
\begin{pmatrix}
0 & \ell_2 \\
\ell_3 & \ell_4
\end{pmatrix}
\begin{pmatrix}
a_2 \\
1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix}
.\]
Clearly, $\mathcal{R}(1,1)$ is not a geometric quotient.

The locus of the points in $\mathcal{T}(1,1)$ which describe the monodromy data for modules in $\mathcal{S}(1,1)$ which are direct sums is the union of the two closed sets $a_1 = a_2 = \ell_2 = \ell_3 = 0$ and $a_1 = a_2 = \ell_1 = \ell_4 = 0$. Let $\mathcal{T}(1,1)^* \subset \mathcal{T}(1,1)$ denote the complement of this locus. This set is the union of the six open subsets given by the inequalities $a_1 \neq 0$, $a_2 \neq 0$, $\ell_2 \neq 0$, $\ell_3 \neq 0$, $\ell_{24} \neq 0$ and $\ell_{34} \neq 0$. The group $\mathbb{G}_m \times \mathbb{G}_m$ acts on each of these open affine sets and the categorical quotient is a geometric quotient and is nonsingular. Therefore the quotient $\mathcal{R}(1,1)^*$ of $\mathcal{T}(1,1)^*$, obtained by gluing the six quotients, is a geometric quotient and nonsingular.

Example. The open subset $\ell_2 \neq 0$ is defined by the variables $\ell_1, \ldots, \ell_4, a_1, a_2$ and relations $0 = -\ell_{23}a_1 + \ell_{24}a_1 - \ell_{13}a_2 - \ell_{14}a_1 - \ell_{13} - 1 = 0$, $\ell_{12} \neq 0$. Division by $\mathbb{G}_m \times \mathbb{G}_m$ is equivalent to the normalisation $\ell_1 = \ell_2 = 1$. Elimination of $\ell_4$ by $\ell_4 = \ell_3 + 1$ yields the equation $\ell_3(a_1 - a_2 + a_1a_2) + a_1 = 0$. This is a nonsingular surface. Using the projection $(\ell_3, a_1, a_2) \mapsto (a_1, a_2)$ one finds that this surface is simply connected.

Similar computations lead to the statements: $\mathcal{R}(1,1)^*$ is a nonsingular geometric quotient and is simply connected. The natural map $\tilde{\mathcal{S}}(1,1)^* \to \mathcal{R}(1,1)^* \times \hat{T}$ is a well defined bijection. The reducible locus $\mathcal{R}(1,1)^*_{\text{red}}$ is the union of four, non intersecting, projective lines.

4. $\alpha = \beta = -1$. The categorical quotient $\mathcal{R}(-1, -1)$ has two singular points, namely $(x_1, x_2, x_3) = (0, 1, -2)$ and $(x_1, x_2, x_3) = (-1, 0, -2)$. As in (3), one defines $\mathcal{T}(-1, -1)^*$ and its
geometric non singular quotient $\mathcal{R}(-1, -1)^*$. The space $\mathcal{R}(-1, -1)^*$ contains four, non intersecting, projective lines. These lines correspond to the reducible locus of $\mathcal{R}(-1, -1)^*$. As in (3) one defines $\tilde{S}(-1, -1)^*$ and concludes:

$\mathcal{R}(-1, -1)^*$ is a nonsingular geometric quotient and is simply connected.

The natural map $\tilde{S}(-1, -1)^* \to \mathcal{R}(-1, -1)^* \times \tilde{T}$ is a bijection.

### 3.4.2 Reducible modules in $S$

We use here the notation of Sections 3.2 and 3.4.1.

**Observations 3.5.** Let $N \subset M$ be a 1-dimensional submodule, then $\mathbb{C}((z)) \otimes N = \mathbb{C}((z))E_i$ and $\mathbb{C}((z^{-1})) \otimes N = \mathbb{C}((z^{-1}))F_j$ with $i, j \in \{1, 2\}$. Since $N$ has no other singularities than 0, $\infty$ one has $N = \mathbb{C}(z)n$ with $\delta(n) = (\pm tz^{-1} + f) n$, where $d \in \mathbb{C}$ is unique modulo $\mathbb{Z}$. Indeed, $\delta(n) = (\pm tz^{-1} + f) n$, where $f \in \mathbb{C}(z)$ has no poles at 0 and $\infty$. Using that $N$ has only singularities at 0 and $\infty$, one can change the generator $n$ of $N$ such that $f$ is a constant $d$. Any other base vector of $N$ with this property has the form $z^k n$ with $k \in \mathbb{Z}$. Further $d \in \pm \theta_\infty/2 + \mathbb{Z}$ and $d \in \pm \theta_\infty/2 + \mathbb{Z}$ and hence $\alpha = \beta^{\pm 1}$.

**Proposition 3.6** (Reducible modules). 1. A module $(M, t) \in S$ is reducible if and only if there are $i, j \in \{1, 2\}$ such that $a_i = 0$, $b_j = 0$ and $L(\mathbb{C}e_i) = \mathbb{C}f_j$.

2. Let $(M, t) \in S$ be reducible, but not a direct sum of two submodules of dimension one. Then there are unique elements $\epsilon_1, \epsilon_2 \in \{-1, 1\}$, a complex number $d$, unique modulo $\mathbb{Z}$, and a polynomial $c = c_1 z + c_0 \neq 0$, unique up to multiplication by a scalar, such that $M$ is represented by the matrix differential operator

$$z \frac{d}{dz} + \left(\begin{array}{cc} -\frac{\epsilon_1 t z^{-1} + \epsilon_2 t z}{c_1 z + c_0} & d \\ \frac{\epsilon_1 t z^{-1} + \epsilon_2 t z}{2} + d & 0 \end{array}\right).$$

3. For $\alpha \neq \pm 1$, the reducible locus $S(\alpha, \alpha)^*_\text{red}$ of $S(\alpha, \alpha)^*$ is represented by the union of the two families in (2) given by $e^{2\pi i d} = \alpha$, $\epsilon_1 = \epsilon_2 = 1$ and $\epsilon_1 = \epsilon_2 = -1$. Each of the two families is isomorphic to $\mathbb{P}^1 \times T$, by sending the matrix differential operator to $((c_1 : c_0), t) \in \mathbb{P}^1 \times T$.

The isomorphism $\tilde{S}(\alpha, \alpha)^*_\text{red} \to \mathcal{R}(\alpha, \alpha)^*_\text{red} \times \tilde{T}$ yields two isomorphism $\mathbb{P}^1 \times \tilde{T} \to \mathbb{P}^1 \times \tilde{T}$. These have the form $(p, \hat{t}) \mapsto (A(\hat{t}) p, \hat{t})$ where $A(\hat{t})$ is an automorphism of $\mathbb{P}^1$, depending on $\hat{t}$.

4. A similar result holds for $\alpha \neq \pm 1$ and $\alpha = \beta^{-1}$.

5. $S(1, 1)^*_\text{red}$ is represented by the families $d \in \mathbb{Z}$ and the four possibilities of $\epsilon_1, \epsilon_2$. Then $S(1, 1)^*_\text{red}$ identifies with the disjoint union of four copies of $\mathbb{P}^1 \times \tilde{T}$. The same holds for $\mathcal{R}(1, 1)^*_\text{red} \times \tilde{T}$. The isomorphism $\tilde{S}(1, 1)^*_\text{red} \to \mathcal{R}(1, 1)^*_\text{red} \times \tilde{T}$ yields four isomorphism $\mathbb{P}^1 \times \tilde{T} \to \mathbb{P}^1 \times \tilde{T}$. These have the form described in (3).

6. The case $\alpha = \beta = -1$ is similar to case (5).

**Proof.** 1. This follows from Observations 3.5 and the statement that a differential module over $\mathbb{C}(z)$ is determined by its monodromy data (i.e., ordinary monodromy, Stokes matrices and links) and the formal classification of the singular points (see [10, Theorem 1.7]).

2. For convenience we consider the case $i = j = 1$ of (1). Using the above Observation, one finds that $M$ has a basis $m_1$, $m_2$ such that $z \partial(m_2) = a m_2$ and $z \partial(m_1) = -a m_1 + f m_2$ with $a := \frac{t z^{-1} + f z}{2} + d$ and $f \in \mathbb{C}(z)$. If we fix $d$, then $m_2$ is unique up to multiplication by a scalar. Further, $m_1$ is unique up to a transformation $m_1 \mapsto \lambda m_1 + h m_2$ with $\lambda \in \mathbb{C}^*$, $h \in \mathbb{C}(z)$. This transformation changes $f$ into $\lambda f + 2 a h + z h'$. We start considering the subgroup of transformations with $\lambda = 1$ and $h \in \mathbb{C}(z)$. For a suitable $h$ the term $f_1 := f + 2 a h + z h'$ has in $\mathbb{C}^*$ at most poles of order one. A pole of order one of $f_1$ in $\mathbb{C}^*$ cannot disappear by a transformation of the form under consideration. Since $M$ has only
singularities at 0 and \(\infty\) we conclude that \(f_1 \in \mathbb{C}[z, z^{-1}]\). For suitable \(h \in \mathbb{C}[z, z^{-1}]\) the term \(c := f_1 + 2ah + zh'\) is a polynomial of degree \(\leq 1\) and is \(\neq 0\), by assumption. For any \(h \in \mathbb{C}(z)\), \(h \neq 0\) the term \(c + 2ah + zh'\) is not a polynomial of degree \(\leq 1\). This yields a unique \(c\) for this subgroup of transformations. Finally, the transformation \(m_1 \mapsto \lambda m_1\) shows that \(c\) is unique up to multiplication by a scalar.

Cases (3)–(6) are consequences of the above computation of the \(\mathcal{R}(\alpha, \beta)_{\text{red}}^*\).

### 3.4.3 The reducible connections in \(\mathcal{M}(\theta_0, \theta_\infty)\)

The image of the injective map \(\mathcal{M}(\theta_0, \theta_\infty) \to \mathcal{S}(\alpha, \beta)^*\), where \(\alpha = e^{\pi i \theta_0}, \beta = e^{\pi i \theta_\infty}\), will be denoted by \(\mathcal{S}(\theta_0, \theta_\infty)\). By Remarks 3.2 part (3), this image contains the irreducible modules \((M, t)\). For \(\alpha \neq \beta \pm 1\), \(\mathcal{S}(\theta_0, \theta_\infty)\) is equal to \(\mathcal{S}(\alpha, \beta) = \mathcal{S}(\alpha, \beta)^*\). Now we consider the other cases.

**Proposition 3.7.** Suppose \(\alpha = \beta \neq \pm 1\). Then \(\mathcal{S}(\theta_0, \theta_\infty)\) consists of:

(a) the irreducible elements \((M, t)\);

(b) the \((\epsilon_1, \epsilon_2) = (1, 1)\) family of reducible modules \(\Leftrightarrow \theta_0 - \theta_\infty \geq 2\);

(c) the \((\epsilon_1, \epsilon_2) = (-1, -1)\) family of reducible modules \(\Leftrightarrow \theta_0 - \theta_\infty \leq 0\).

**Proof.** Part (a) is known. Consider an element \((M, t)\) in the \((\epsilon_1, \epsilon_2) = (1, 1)\) family of reducible modules. Let the connection \((\mathcal{V}, \nabla)\), corresponding to \((M, t)\), be defined as in Section 3.3.1. Then \(\mathcal{V}\) can be identified with the vector bundle \(O(k[0])e_1 + O((-k - 1)[0])e_2\) for some integer \(k \geq 0\). Then \((M, t)\) lies in \(\mathcal{S}(\theta_0, \theta_\infty) \iff k = 0\).

Consider the case \(k > 0\). Then \(\nabla_{\frac{d}{dz}} e_1 = (a_{-1} z^{-1} + a_0 + a_1 z) e_1\) and \(\nabla_{\frac{d}{dz}} (z^{-k} e_1) = (a_{-1} z^{-1} + a_0 + a_1 z - k)(z^{-k} e_1)\).

Comparing with the prescribed local operator at \(z = 0\) yields the possibilities: \(a_{-1} z^{-1} + a_0\) equals (i) \(\frac{t}{2} z^{-1} + \frac{\theta_0}{2}\) or (ii) \(-\frac{t}{2} z^{-1} - \frac{\theta_0}{2} + 1\).

Comparing with the prescribed local operator at \(z = \infty\) yields the possibilities: \(a_0 + a_1 z\) equals (A) \(\frac{t}{2} z + \frac{\theta_\infty}{2}\) or (B) \(-\frac{t}{2} z - \frac{\theta_\infty}{2}\). Combining one obtains

\[
(i), \quad (A) \quad a_{-1} = \frac{t}{2}, \quad a_1 = \frac{t}{2}, \quad \theta_0 = \theta_\infty - 2k, \quad (\epsilon_1, \epsilon_2) = (1, 1),
\]

\[
(i), \quad (B) \quad a_{-1} = \frac{t}{2}, \quad a_1 = -\frac{t}{2}, \quad \theta_0 = -\theta_\infty - 2k, \quad (\epsilon_1, \epsilon_2) = (1, -1),
\]

\[
(ii), \quad (A) \quad a_{-1} = -\frac{t}{2}, \quad a_1 = \frac{t}{2}, \quad \theta_0 = -\theta_\infty + 2k + 2, \quad (\epsilon_1, \epsilon_2) = (-1, 1),
\]

\[
(ii), \quad (B) \quad a_{-1} = -\frac{t}{2}, \quad a_1 = -\frac{t}{2}, \quad \theta_0 = \theta_\infty + 2k + 2, \quad (\epsilon_1, \epsilon_2) = (-1, -1).
\]

Since \(\alpha = \beta \neq \pm 1\), reducible modules of types \((1, -1)\) and \((-1, 1)\) are not present in \(\mathcal{S}(\alpha, \alpha)^*\). Now we consider the presence of reducible modules of type \((1, 1)\) in \(\mathcal{S}(\theta_0, \theta_\infty)\). The condition \(\theta_0 - \theta_\infty \geq 0\) is necessary because of \((i), A)\).

Consider the case \(\theta_0 = \theta_\infty = 2d\). A reducible module of type \((1, 1)\) yields a connection on \(\mathcal{W} = O f_1 \oplus O f_2\) with the local data \(z \frac{d}{dz} + \begin{pmatrix} -\frac{1}{2} z^{-1} + d & 0 \\ \frac{1}{2} z^{-1} + d & -\frac{1}{2} \end{pmatrix}\) at \(z = 0\) and \(z \frac{d}{dz} + \begin{pmatrix} -\frac{1}{2} z + d & 0 \\ \frac{1}{2} z + d & -\frac{1}{2} \end{pmatrix}\) at \(z = \infty\). Now \(\mathcal{V} = O(-[0]) f_1 \oplus O f_2 = O e_1 \oplus O(-[0]) e_2\), with \(e_1 = f_2, e_2 = f_1\), has the required local data and the matrix of \(\nabla_{\frac{d}{dz}}\) with respect to the basis \(e_1, e_2\) is \(\begin{pmatrix} \omega & * \\ 0 & -\omega \end{pmatrix}\). Thus \(c_0 = c_1 = 0\) and the reducible modules of type \((1, 1)\) are not present according to the construction of \(\mathcal{M}(\theta_0, \theta_\infty)\).
Consider the case $\theta_0 = \theta_\infty + 2$. The standard form of Proposition 3.6.2 for type (1, 1) belongs to $\mathcal{M}(2d + 2, 2d)$. Further, see Remarks 3.2.3, $(c_0, c_1) \neq (0, 0)$ holds for $\theta_0 - \theta_\infty > 2$. This proves (b). The proof of (c) is similar.

Similarly one shows: $\alpha = \beta^{-1} \neq \pm 1$. Then $\mathcal{S}(\theta_0, \theta_\infty)$ consists of:

(a) the irreducible elements $(M, t)$;
(b) the $(\epsilon_1, \epsilon_2) = (1, -1)$ family of reducible modules $\Leftrightarrow \theta_0 + \theta_\infty \geq 2$;
(c) the $(\epsilon_1, \epsilon_2) = (-1, 1)$ family of reducible modules $\Leftrightarrow \theta_0 + \theta_\infty \leq 0$.

$\alpha = \beta = \pm 1$. Then $\mathcal{S}(\theta_0, \theta_\infty)$ consists of:

(a) the irreducible elements $(M, t)$;
(b) the $(\epsilon_1, \epsilon_2) = (1, 1)$ family of reducible modules $\Leftrightarrow \theta_0 - \theta_\infty \geq 2$;
(c) the $(\epsilon_1, \epsilon_2) = (1, -1)$ family of reducible modules $\Leftrightarrow \theta_0 + \theta_\infty \geq 2$;
(d) the $(\epsilon_1, \epsilon_2) = (-1, 1)$ family of reducible modules $\Leftrightarrow \theta_0 - \theta_\infty \leq 0$;
(e) the $(\epsilon_1, \epsilon_2) = (-1, -1)$ family of reducible modules $\Leftrightarrow \theta_0 - \theta_\infty \leq 0$.

3.4.4 $\mathcal{M}(\theta_0, \theta_\infty)$ for $\alpha = \beta^{\pm 1}$

Let $\mathcal{R}(\theta_0, \theta_\infty)$ denote the open subspace of $\mathcal{R}(\alpha, \beta)^*$ which corresponds to the subset $\mathcal{S}(\theta_0, \theta_\infty)$ of $\mathcal{S}^*(\alpha, \beta)$, defined in Section 3.4.3. By Sections 3.4.1–3.4.3, the extended Riemann–Hilbert morphism $\tilde{\mathcal{M}}(\theta_0, \theta_\infty) \rightarrow \mathcal{R}(\theta_0, \theta_\infty) \times \tilde{T}$ is a well defined analytic isomorphism. This has as consequence:

**Theorem 3.3** holds for the cases $\frac{\theta_0}{2} \pm \frac{\theta_\infty}{2} \in \mathbb{Z}$ with $\mathcal{R}(\alpha, \beta)$ replaced by $\mathcal{R}(\theta_0, \theta_\infty)$.

3.4.5 Isomonodromy for reducible connections

The fibers of the locally defined map $\mathcal{S}(\alpha, \alpha^{\pm 1})_{\text{red}} \rightarrow \mathcal{R}(\alpha, \alpha^{\pm 1})_{\text{red}}$ are the isomonodromy families of reducible modules. As a start, we consider the reducible family of type $(\epsilon_1, \epsilon_2) = (1, 1)$ lying in $\mathcal{M}(2d + 2, 2d)$. This family is represented by $z \frac{d}{dz} + \left( -\frac{tz^{-1+tz}}{2} - d \frac{0}{z-q} \frac{tz^{-1+tz}}{2} + d \right)$. For an isomonodromy subfamily of this, $q$ is a function of $t$ and the Stokes data at 0 and $\infty$ and the link are fixed. Isomonodromy is equivalent to the statement that the above matrix differential operator commutes with an operator of the form $\frac{d}{dt} + B_{-1}z + B_0 + B_1z$, where the tracefree $2 \times 2$ matrices $B_{-1}$, $B_0$, $B_1$ depend on $t$ only. This leads to the equation

\[
\begin{pmatrix}
-z^{-1+tz}
& 0 \\
-d & z^{-1+tz}
\end{pmatrix} = -B_1z^{-1} + B_1z
\]

\[
- \left[ B_{-1}z^{-1} + B_0 + B_1z, \left( -\frac{tz^{-1+tz}}{2} - d \frac{0}{z-q} \frac{tz^{-1+tz}}{2} + d \right) \right].
\]

A computation yields the equation $q' = -2q^2 - \frac{4d-1}{4}q - 2$. The solutions of this equation have the form $\frac{1}{2} \frac{y'}{y}$, where $y$ is a non zero solution of the Bessel equation $y'' + \frac{4d-1}{4}y' + 4y = 0$. One obtains in a similar way for an isomonodromic family of reducible modules of type $(\epsilon_1, \epsilon_2)$ the equation

\[
q' = -2\epsilon_2q^2 - \frac{4d-1}{4}q - 2\epsilon_1.
\]
The solutions are \( q = \frac{\Omega y'}{y} \) where \( y \) is a solution of the Bessel equation \( y'' + \frac{4d+1}{t}y' + 4\epsilon_1\epsilon_2y = 0 \). These equations are consistent with the formula of Theorem 3.3
\[
q'' = \frac{(q')^2}{q} - \frac{q'}{t} - \frac{4(\theta_0 - 1)}{t} + \frac{4\theta_\infty q^2}{t} + 4q^2 - \frac{4}{q}
\]
for isomonodromic families in \( \mathcal{M}(\theta_0, \theta_\infty) \). According to [5] we found in this way all Riccati solutions for PIII(D_6), up to the action of the Bäcklund transformations.

**Remark 3.8.** The assumption that a function \( q \) satisfies two distinct PIII(D_6) equations leads to \( q^4 = 1 \). Thus we found the algebraic solutions \( q = \pm 1 \) for \( \theta_\infty = \theta_0 - 1 \) and \( q = \pm i \) for \( -\theta_\infty = \theta_0 - 1 \). According to [5] these are all the algebraic solutions of PIII(D_6), up to the action of the Bäcklund transformations.

## 4 Bäcklund Transformations for PIII(D_6)

### 4.1 Automorphisms of \( S \)

We start with a table of generators for the group \( \text{Aut}(S) \) of ‘natural’ automorphism of \( S \), in terms of their action on the parameters \( \alpha, \beta \) and on \( t, z \).

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( t )</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_1 )</td>
<td>( \alpha^{-1} )</td>
<td>( \beta^{-1} )</td>
<td>(-t)</td>
<td>( z )</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>( -\alpha )</td>
<td>(-\beta )</td>
<td>( t )</td>
<td>( z )</td>
</tr>
<tr>
<td>( \sigma_3 )</td>
<td>( \alpha )</td>
<td>( \beta^{-1} )</td>
<td>( it )</td>
<td>( iz )</td>
</tr>
<tr>
<td>( \sigma_4 )</td>
<td>( \beta )</td>
<td>( \alpha )</td>
<td>( t )</td>
<td>( z^{-1} )</td>
</tr>
</tbody>
</table>

These generators are defined as follows.

1. \( \sigma_1 : (M, t) \mapsto (M, -t) \). This induces bijections \( S(\alpha, \beta) \to S(\alpha^{-1}, \beta^{-1}) \). Indeed, the basis vectors \( e_1, e_2 \) of \( V(0) \) are interchanged and the same holds for the basis \( f_1, f_2 \) of \( V(\infty) \).

2. Define the differential module \( N = C(z)b \) by \( db = \frac{1}{2}b \). Then \( \sigma_2 : (M, t) \mapsto (M \otimes N, t) \). Since \( \Lambda^2(M \otimes N) = N \otimes^2 \) is the trivial module, \( (M \otimes N, t) \) belongs to \( S \). Let \( E_1, E_2 \) be a basis of \( C((z)) \otimes M \) such that \( \delta E_1 = -\frac{t-1+\theta_0}{2}E_1 \) and \( \delta E_2 = \frac{t-1+\theta_0}{2}E_2 \). Then the formal module \( C((z)) \otimes (M \otimes N) \) has basis \( E_1 \otimes b, E_2 \otimes b \) and \( \delta(E_1 \otimes b) = (\frac{t-1+\theta_0}{2} + \frac{1}{2})(E_1 \otimes b) \) and similarly \( \delta(E_2 \otimes b) = (\frac{t-1+\theta_0}{2} + \frac{1}{2})(E_2 \otimes b) \). Thus \( e^{\pi i(\theta_0 + 1)} = -\alpha \) is the eigenvalue of the formal monodromy at \( z = 0 \). The same argument shows that \( -\beta \) is the eigenvalue of the formal monodromy at \( z = \infty \).

3. Let \( \phi \) be a \( C \)-linear automorphism of the field \( C(z) \), such that \( z \frac{d}{dz} \circ \phi = \mu \cdot \phi \circ z \frac{d}{dz} \) for some \( \mu \in C^* \). There are two possibilities:

   (a) \( \phi(z) = cz \) with \( c \in C^*, \mu = 1 \), (b) \( \phi(z) = cz^{-1} \) with \( c \in C^*, \mu = -1 \).

   For \( (M, t) \in S \) one considers \( (C(z) \otimes_M M, \ldots, ) \). As additive group \( C(z) \otimes_M M \) is identified with \( M \). Its structure as vector space is given by the new scalar multiplication \( f \ast m := \phi(f)m \). In case (a), the differential structure is given by the original \( \delta \) and in case (b) the differential structure is given by \( -\delta \).

   (a) \( \phi(z) = cz \). The formal local module \( C((z)) \otimes M \) with basis \( E_1, E_2 \) and \( \delta E_1 = -\frac{t-1+\theta_0}{2}E_1 \), \( \delta E_2 = \frac{t-1+\theta_0}{2}E_2 \) is transformed into \( C((z)) \otimes \sigma M \). Now \( \delta E_1 = -\frac{tcz^{-1}+\theta_0}{2}E_1 \) and \( \delta E_2 = \frac{tcz^{-1}+\theta_0}{2}E_2 \). The basis \( F_1, F_2 \) of \( C((z^{-1})) \otimes M \) with \( \delta F_1 = -\frac{tcz^{-1}+\theta_\infty}{2}F_1 \) and \( \delta F_2 = \frac{tcz^{-1}+\theta_\infty}{2}F_2 \), yields for the new structure the formulas \( \delta F_1 = -\frac{tcz^{-1}+\theta_\infty}{2}F_1 \) and \( \delta F_2 = \frac{tcz^{-1}+\theta_\infty}{2}F_2 \).

   The condition \( tc = \pm t \) implies that \( c^4 = 1 \). We define \( \sigma_3 \) by \( \phi(z) = iz \). This yields the new module \( C(z) \otimes_M (it) \) with new \( \alpha \) equal to \( e^{\pi i\theta_0} \) and new \( \beta \) equal to \( e^{-\pi i\theta_\infty} \).
(b) We define $\sigma_4$ by $\phi(z) = z^{-1}$. The new module $(\mathbb{C}(z) \otimes \phi, M, t)$ has new $\alpha = e^{\pi i \theta \infty}$ and new $\beta = e^{\pi i \theta_0}$.

Comments. Using the first three columns of the table we will consider $\text{Aut}(S)$ as an automorphism group of the algebraic variety $\mathbb{C}^* \times \mathbb{C}^* \times \mathbb{C}^*$. A straightforward computation shows that $\text{Aut}(S)$ is the product $\langle \sigma_1 \rangle \times \langle \sigma_2 \rangle \times \langle \sigma_3, \sigma_4 \rangle$, where $\langle \sigma_1 \rangle$ and $\langle \sigma_2 \rangle$ have order two and $\langle \sigma_3, \sigma_4 \rangle$ is the dihedral group $D_4$ of order eight.

The action of $\text{Aut}(S)$ on the monodromy data.

1. $\sigma_1$. The map $t \mapsto -t$ has as consequence that the basis vectors $e_1, e_2$ of $V(0)$ are permuted and the same holds for $V(\infty)$. The singular directions and the Stokes maps do not change. The new topological monodromies are $\left(\frac{1+\alpha_1 \alpha_2}{\alpha a_2} \right)$ at $z = 0$ and $\left(\frac{1+\beta b_2}{\beta b_2} \right)$ at $z = \infty$. The matrix of the link $L$ is now $\left(\ell_4 \ell_3 \ell_2 \ell_1\right)$. The matrix relation remains the same. This amounts to the change $\alpha \mapsto \alpha^{-1}$, $\beta \mapsto \beta^{-1}$, $a_1 \mapsto a_2$, $b_1 \mapsto b_2$, $\ell_1 \mapsto \ell_4$, $\ell_2 \mapsto \ell_3$. This induces an automorphism of $R$ given by the formula $(\alpha, \beta, x_1, x_2, x_3) \mapsto (\alpha^{-1}, \beta^{-1}, x_1 \alpha^{-1} \beta^{-1}, x_2 \alpha^{-1} \beta^{-1}, x_3)$.

2. $\sigma_2$. The map $(M, t) \mapsto (M \otimes N, t)$ has as consequence that the formal monodromies at $z = 0$ and $z = \infty$ are multiplied by $\left(-1 0 0\right)$ (and thus $\alpha \mapsto -\alpha$, $\beta \mapsto -\beta$). The Stokes matrices do not change. The same holds for the link $L$. The induced automorphism of $R$ is given by the formula $(\alpha, \beta, x_1, x_2, x_3) \mapsto (-\alpha, -\beta, x_1, -x_2, -x_3)$.

3. $\sigma_3$. The effect of this transformation is: the singular directions change over $\frac{\pi i}{2}$; the basis vectors of $V(0)$ are permuted; the basis of $V(\infty)$ is unchanged; the Stokes map and the link remain the same, however the corresponding matrices change. The induced automorphism of $R$ is given by $(\alpha, \beta, x_1, x_2, x_3) \mapsto (\alpha^{-1}, \beta, \alpha^{-1} x_1, \alpha^{-1} x_2, x_3)$.

4. $\sigma_4$. The spaces $V(0)$ and $V(\infty)$ are interchanged; the other data are unchanged. The induced automorphism of $R$ is given by $(\alpha, \beta, x_1, x_2, x_3) \mapsto (\beta, \alpha, x_1, x_2, x_3)$.

4.2 Bäcklund transformations

Define the map $\exp : \mathbb{C}^3 \to (\mathbb{C}^*)^3$ by $(\theta_0, \theta_\infty, \hat{t}) \mapsto (\alpha, \beta, t) := (e^{\pi i \theta_0}, e^{\pi i \theta \infty}, e^{\hat{t}})$. We will define the group $B(S)$ of the Bäcklund transformations as the affine automorphisms of $\mathbb{C}^3$ which respect the equivalence relation defined by $\exp$ and which map to elements of $\text{Aut}(S)$. By definition there is an exact sequence of groups $0 \to B(S)_0 \to B(S) \to \text{Aut}(S) \to 1$, where $B(S)_0$ is the group of affine transformations of $\mathbb{C}^3$, generated by: $B_1 : (\theta_0, \theta_\infty, \hat{t}) \mapsto (2 + \theta_0, \theta_\infty, \hat{t})$, $B_2 : (\theta_0, \theta_\infty, \hat{t}) \mapsto (\theta_0, 2 + \theta_\infty, \hat{t})$ and $B_3 : (\theta_0, \theta_\infty, \hat{t}) \mapsto (\theta_0, \theta_\infty, 2\pi i + \hat{t})$.

The aim is to give each Bäcklund transformation the interpretation of a morphism between the various moduli spaces $\mathcal{M}(\ast, \ast)$, preserving the foliations by isomonodromic families, and to compute the effect on solutions of $\text{PIII}(D_6)$. First we investigate the group $B(S)$.

The affine map $B_3$ is not considered in the literature. Its action on $\hat{t}$ is obvious since $\mathcal{M}(\theta_0, \theta_\infty) = \mathcal{M}(\theta_0, \theta_\infty) \times T \hat{T}$ and $\hat{T} = T \cong T = \mathbb{C}^*$ is the map $\hat{t} \mapsto e^{\hat{t}}$. The effect of $B_3$ on solutions of $\text{PIII}(D_6)$ is far from obvious. A solution is a function $q(\hat{t}) = "q(e^{\hat{t}})"$. Since the equation depends only on $t$, the function $q(2\pi i + \hat{t})$ satisfies the same equation. It seems that no formula for $q(2\pi i + \hat{t})$ in terms of $q(\hat{t})$ and its derivative is present in the literature.

Generators for $B(S)$ are given by their action on $\mathbb{C}^3$ and the variables $t, z$. 

<table>
<thead>
<tr>
<th></th>
<th>$\theta_0$</th>
<th>$\theta_\infty$</th>
<th>$\hat{t}$</th>
<th>$t$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1$</td>
<td>$2 - \theta_0$</td>
<td>$-\theta_\infty$</td>
<td>$\pi i + \hat{t}$</td>
<td>$-t$</td>
<td>$z$</td>
</tr>
<tr>
<td>$s_2$</td>
<td>$1 + \theta_0$</td>
<td>$1 + \theta_\infty$</td>
<td>$\hat{t}$</td>
<td>$t$</td>
<td>$z$</td>
</tr>
<tr>
<td>$s_3$</td>
<td>$\theta_0$</td>
<td>$-\theta_\infty$</td>
<td>$\frac{\pi i}{2} + \hat{t}$</td>
<td>$it$</td>
<td>$iz$</td>
</tr>
<tr>
<td>$s_4$</td>
<td>$\theta_\infty$</td>
<td>$\theta_0$</td>
<td>$\hat{t}$</td>
<td>$t$</td>
<td>$z^{-1}$</td>
</tr>
</tbody>
</table>
These elements generate $B(S)$ because: $s_*$ is mapped to $\sigma_*$ for $* = 1, 2, 3, 4$; $B_3 = s_1^2 = s_3^4$; $B_1 = s_3 s_1^{-1} s_4 s_3 s_4$ and $B_2 = B_1^{-1} s_2^2$.

The group $\langle B_3 \rangle$, generated by $B_3$, is isomorphic to $\mathbb{Z}$ and lies in the center of $B(S)$. Put $B(S) = B(S)/\langle B_3 \rangle$ and let $\overline{s}_*$ denote the image of $s_*$ in this quotient. Then $\overline{s}_3^3$ has order two and lies in the center of $\overline{B}(S)$.

We compare this with Okamoto’s paper [7]. The group of the Bäcklund transformations $B$ of equation $\Pi_{\Phi}$ of degree two covering of $P_{\Phi}$ is computed to be the affine Weyl group of type $B_2$. These elements generate $B_2$.

In contrast to this, the new transformations of [13] do not seem to have a simple modular interpretation. In a sense, $\Pi_{\Phi}(D_6)$ is a degree two covering of $\Pi_{\Phi}(D_6)$. It can be seen that there is a surjective homomorphism $\overline{B}(S) \rightarrow B$ with kernel $\langle \overline{s}_3^3 \rangle$.

Our approach using moduli spaces explains the Bäcklund transformations presented in [4]. In contrast to this, the new transformations of [13] do not seem to have a simple modular interpretation.

### 4.3 Bäcklund transformations of the moduli spaces

Let $s \in B(S)$ have image $\sigma \in \text{Aut}(S)$. Choose $\alpha$, $\beta$ and write $\alpha' = \sigma(\alpha)$, $\beta' = \sigma(\beta)$. Choose $\theta_0$, $\theta_\infty$, $\theta'_0$, $\theta'_\infty$ such that $e^{\pi i \theta_0} = \alpha$, ..., $e^{\pi i \theta_\infty} = \beta$ and $s(\theta_0) = \theta'_0$, $s(\theta_\infty) = \theta'_\infty$. Now $\sigma$ induces a bijection $S(\alpha, \beta) \xrightarrow{\sigma} S(\alpha', \beta')$ and consider

$$
\mathcal{M}(\theta_0, \theta_\infty) \rightarrow S(\alpha, \beta) \xrightarrow{\sigma} S(\alpha', \beta') \leftarrow \mathcal{M}(\theta'_0, \theta'_\infty).
$$

The first and the last arrow are injective. Their images contain the locus of the irreducible modules and the loci of the $(e_1, e_2)$-reducible modules depending on the $\theta_0, \ldots, \theta_\infty$ (see Section 3.4.3). Thus we obtain a, maybe partially defined, map, again denoted by $s : \mathcal{M}(\theta_0, \theta_\infty) \rightarrow \mathcal{M}(\theta'_0, \theta'_\infty)$.

It can be seen from the definitions of the elements of $\text{Aut}(S)$ that the Bäcklund transformation $s$ is a birational algebraic map. Using the expression for $s(\ell)$ one obtains a birational morphism, again denoted by $s : \mathcal{M}(\theta_0, \theta_\infty) \rightarrow \mathcal{M}(\theta'_0, \theta'_\infty)$ which respects the foliations (i.e., the isomonodromic families). In particular, $s$ maps ‘generic’ solutions for the parameters $\theta_0, \theta_\infty$ and the variable $\ell$ to ‘generic’ solutions for the parameters $\theta'_0, \theta'_\infty$ and the variable $s(\ell)$. The term ‘generic’ means here the solutions corresponding to irreducible modules and the ones for $(e_1, e_2)$-reducible modules (i.e., Riccati solutions) which are present in both $\mathcal{M}(\theta_0, \theta_\infty)$ and $\mathcal{M}(\theta'_0, \theta'_\infty)$.

### 4.4 Formulas for the Bäcklund transformations

#### 4.4.1 $s_1 : \mathcal{M}(\theta_0, \theta_\infty) \rightarrow \mathcal{M}(2 - \theta_0, -\theta_\infty)$

Using the first charts of the two spaces and their variables, $s_1$ has the form $(a_{-1}, b_{-2}, \ldots, b_1, c_0, \ell) \mapsto (a_{-1}, b_{-2}, \ldots, b_1, c_0, \ell + i\pi)$. The formula for $s_1$ on the second charts is similar. The induced map for the $\Pi_{\Phi}(D_6)$ equations is $t \mapsto -t, \frac{d}{dt} \mapsto -\frac{d}{dt}, q(\ell) \mapsto q(\ell + i\pi)$. 
4.4.2 \( s_2 : \mathcal{M}(\theta_0, \theta_\infty) \to \mathcal{M}(1 + \theta_0, 1 + \theta_\infty) \)

A point on the first chart of the first space is represented by the differential operator \( z \frac{d}{dz} + \left( \frac{az^{-1}b}{z - q - az^{-1}} \right) \), where \( a := a_{-1}, q := -c_0, b = b_1 z + b_0 + b_{-1} z^{-1} + b_{-2} z^{-2} \) and the \( b_1, \ldots, b_2 \) are polynomials in \( t, q, q^{-1} \), using the notation of Section 3.3.1. This is transformed by \( s_2 \) into the operator \( z \frac{d}{dz} + A \) with \( A = \left( \frac{az^{-1} + \frac{1}{2}b}{z - q - az^{-1} + \frac{1}{2}} \right) \). We want to compute an operator \( \frac{d}{dz} + \tilde{A} \) with \( \tilde{A} = \left( \frac{\tilde{a}z^{-1}}{z - \tilde{q} - \tilde{a}z^{-1}}, \frac{\tilde{b}}{-\tilde{a}z^{-1}} \right) \), \( \tilde{b} = \tilde{b}_1 z + \tilde{b}_0 + \tilde{b}_{-1} z^{-1} + \tilde{b}_{-2} z^{-2} \) and \( \tilde{b}_1, \ldots, \tilde{b}_2 \) polynomials in \( t, \tilde{q}, \tilde{q}^{-1} \), representing a point on the first chart of \( \mathcal{M}(\tilde{\theta}_0, \tilde{\theta}_\infty) \) with \( \tilde{\theta}_0, \tilde{\theta}_\infty \) in the first chart. A Maple computation shows that there is a unique solution in terms of \( \tilde{\theta}_\infty \), \( q \in \mathbb{T} \), \( t \in \mathbb{T} \), \( a \in \mathbb{T} \), \( b \in \mathbb{T} \), \( c \in \mathbb{T} \), \( d \in \mathbb{T} \).

**Comments on the formulas.** The term \( q \) in the denominator of the formulas is due to our choice of working on the first charts of the spaces \( \mathcal{M}(\theta_0, \theta_\infty) \) and \( \mathcal{M}(\theta_0 + 1, \theta_\infty + 1) \). This term does not produce singularities for \( s_2 \).

The denominator \( (tq^2 + q \theta_\infty - t + 2a) \) is due to a reducible locus of type \((e_1, e_2) = (-1, 1)\). More precisely, \( tq^2 + q \theta_\infty - t + 2a = 0 \) describes the reducible locus of \( \mathcal{M}(\theta_0, \theta_\infty) \) if and only if \( \theta_0 + \theta_\infty \in 2\mathbb{Z} \) and \( \theta_0 + \theta_\infty \leq 0 \).

**A priori**, \( s_2 \) is not defined on this locus if moreover \( \theta_0 + \theta_\infty = 0 \). One computes that for \( \theta_\infty + \theta_0 = 0 \) the formulas reduce to the rational map \( \tilde{q} = -q^{-1}, \tilde{a} = \frac{-a + 2a}{2t} \) and thus \( s_2 \) is well defined on this locus of type \((e_1, e_2) = (-1, 1)\). In fact, \( s_2 \) maps this locus to the reducible locus of type \((e_1, e_2) = (1, -1)\), which is present in \( \mathcal{M}(\theta_0 + 1, \theta_\infty + 1) \).

4.4.3 \( s_3 : \tilde{\mathcal{M}}(\theta_0, \theta_\infty) \to \tilde{\mathcal{M}}(\theta_0, -\theta_\infty) \)

On the first charts the map is given by: \((a_{-1}, b_{-2}, \ldots, b_1, c_0, \tilde{t}) \mapsto (-ia_{-1}, -ib_{-2}, b_{-1}, ib_0, -b_1, -ic_0, \tilde{t} + i\frac{\pi}{2})\) and similarly on the second charts. For the PIII(D_0) equations, the map is \( t \mapsto it, \frac{d}{dt} \mapsto -i\frac{d}{dt}, q(\tilde{t}) \mapsto -iq(\tilde{t} + i\frac{\pi}{2}) \).

4.4.4 \( s_4 : \mathcal{M}(\theta_0, \theta_\infty) \to \mathcal{M}(\theta_\infty, \theta_0) \)

Consider a point on the chart \( c_1 \neq 0 \) of \( \mathcal{M}(\theta_0, \theta_\infty) \) (see Section 3.3.1) represented by \( z \frac{d}{dz} + A(z) \), where the entries of \( A(z) \) are polynomial in \( z, z^{-1}, t, a := a_{-1}, q := -c_0, q^{-1} \). Now \( s_4 \) transforms this operator into \( z \frac{d}{dz} - A(z^{-1}) \). We suppose that a transformation \( T := T_{-1} z^{-1} + T_0 + T_1 z \neq 0 \) brings this operator into a point of the chart \( c_1 \neq 0 \) of \( \mathcal{M}(\theta_\infty, \theta_0) \) represented by an operator \( z \frac{d}{dz} + \tilde{A}(z) \), where the entries of \( \tilde{A}(z) \) are polynomials in \( z, z^{-1}, t, \tilde{a} = \tilde{a}_{-1}, \tilde{q} = -\tilde{c}_0, \tilde{q}^{-1} \). A Maple computation shows that there is a unique solution in terms of \( \tilde{q} \) and \( \tilde{a} \) of the equation.
{z \frac{d}{dz} - A(z^{-1})}T = T\{z \frac{d}{dz} + \tilde{A}(z)\}, \text{ namely}

\tilde{q} = \frac{q(-q^2t - \theta_\infty q - t + 2a)}{(-q^2t - \theta_0q - t + 2a)}, \quad \tilde{a} = \frac{\text{long}}{2(-q^2t - \theta_0q - t + 2a)^2},

\text{long} = 4q^2at^2 + q^2\theta_0 + q^4t^2\theta_\infty + 4q^3at\theta_0 - q^4t^2\theta_0 - q^4t\theta_\infty \theta_0 - q^2t\theta_0\theta_\infty + 4qt\theta_\infty a

\text{and } 2q^4t^2 + q^4t\theta_\infty - t^2q\theta_\infty - 4q^2t^2q^2 - 4at^2q^2\theta_\infty - 8a^2t^2 + 2aq^4t^2

+ 2at^2 - 8a^2t^2 + 8a^3.

The induced map for solutions of PIII(D6) is obtained from the formula for \( \tilde{q} \) and the equality \( q' = \frac{4a-t}{4+\tilde{q}} \).

Comments on the formulas. The denominator in these formulas is due to a possible reducible locus of type \((\epsilon_1, \epsilon_2) = (-1, -1)\). This locus is present in \( \mathcal{M}(\theta_0, \theta_\infty) \) if and only if \( \theta_0 - \theta_\infty \in 2\mathbb{Z} \) and \( \theta_0 - \theta_\infty \leq 0 \). This locus is not present in \( \mathcal{M}(\theta_\infty, \theta_0) \) if moreover \( \theta_0 - \theta_\infty < 0 \). However, in the critical case \( \theta_0 = \theta_\infty \), \( s_4 \) turns out to be the identity.

If \( \theta_0 - \theta_\infty \in 2\mathbb{Z} \) and \( \theta_0 - \theta_\infty \geq 2 \), then the reducible modules of type \((1, 1)\) are present in \( \mathcal{M}(\theta_0, \theta_\infty) \) and not in \( \mathcal{M}(\theta_\infty, \theta_0) \). The corresponding term \( 2a + tq^2 + (2d - 1)q + t \) in the denominator of the map \( s_4 \) does not occur, because \( s_4 \) maps this reducible locus to the reducible locus of type \((1, -1)\) of \( \mathcal{M}(\theta_\infty, \theta_0) \).

Using the formulas for \( s_1, \ldots, s_4 \) one can deduce formulas for \( B_1 \) and \( B_2 \). We will however derive these by the direct method used for \( s_2 \) and \( s_4 \).

4.4.5 The transformation \( B_1 : \theta_0 \mapsto 2 + \theta_0, \theta_\infty \mapsto \theta_\infty, \tilde{t} \mapsto \tilde{t} \)

We compute the birational map \( B_1 \) on the open part of the chart \( c_1 \neq 0 \) of \( \mathcal{M}(\theta_0, \theta_\infty) \) where \( q = -c_0 \neq 0 \) (see Section 3.3.1). A point is represented by an operator \( z \frac{d}{dz} + A \). The entries of \( A \) are polynomials in \( q = -c_0 \), \( q^{-1} \) and \( a = a_1 \). Further we suppose that the image under \( B_1 \) lies in the open part of \( \mathcal{M}(2 + \theta_0, \theta_\infty) \) given by \( c_1 \neq 0 \) and has the form \( z \frac{d}{dz} + \tilde{A} \), where the entries of \( \tilde{A} \) are polynomials in \( \tilde{q}, \tilde{q}^{-1} \) and \( \tilde{a} = \tilde{a}_1 \). Since the two differential operators represent the same differential module, there exists a \( T \in \text{GL}(2, \mathbb{C}) \) such that \( z \frac{d}{dz} + \tilde{A} = T^{-1}(z \frac{d}{dz} + A)T \).

Local calculations at \( z = 0 \) and \( z = \infty \) predict that \( T \) has the form \( T = T_{-2} z^{-2} + T_{-1} z^{-1} + T_0 \), \( T_{-2} = \begin{pmatrix} 0 & * \\ 0 & 0 \end{pmatrix} \) and \( \text{det } T \in \mathbb{C}^* \).

Further it is assumed that \( z \frac{d}{dz} + A \) is not \((\epsilon_1, \epsilon_2)\)-reducible for the critical cases \((\epsilon_1, \epsilon_2) = (-1, -1), \theta_\infty = \theta_0 \) and \((\epsilon_1, \epsilon_2) = (-1, 1), \theta_\infty = -\theta_0 \), where this reducible locus is present in \( \mathcal{M}(\theta_0, \theta_\infty) \) and not in \( \mathcal{M}(2 + \theta_0, \theta_\infty) \). Maple produces the formulas

\( \tilde{q} = \frac{q(-4a^2 + 4at - t^2 + \theta_0^2q^2 + 4t\theta_\infty q^3 + t^2q^4)}{(2a - t - \theta_0q + tq^2)(2a - t - \theta_0q - tq^2)}, \)

\( \tilde{a} = \frac{\text{long}}{(2a - t - \theta_0q + tq^2)^2(2a - t - \theta_0q - tq^2)^2} \),

where “long” means too long for copying. Substitution of \( a = \frac{tq^2}{4} \) in the formula for \( \tilde{q} \) yields the formula for \( B_1 \) with respect to solutions.

In the first critical case \((\epsilon_1, \epsilon_2) = (-1, -1), \theta_\infty = \theta_0 \) one obtains

\( \tilde{q} = -\frac{q(2a - t + \theta_0q + tq^2)}{2a - t - \theta_0q + tq^2}, \quad \tilde{a} = \frac{\text{long}}{(2a - t - \theta_0q + tq^2)^2} \).

The reducible locus is given by \( a = \frac{t}{2} + \frac{\theta_0}{2}q + \frac{4}{2}q^2 \). Thus the above map extends to the reducible locus and produces there the formulas

\( \tilde{q} = -\frac{q(2tq + 2\theta_0 + 1)}{2tq + 1}, \quad \tilde{a} = \frac{\text{long}}{(2tq + 1)^2} \).
For the second critical case \((\epsilon_1, \epsilon_2) = (-1, 1)\), one finds
\[
\tilde{q} = \frac{q(-2a + t - \theta_0 q + tq^2)}{2a - t - \theta_0 q - t q^2}, \quad \tilde{a} = \frac{\text{long}}{(2a - t - \theta_0 q + t q^2)^2}.
\]

The reducible locus is given by \(a = \frac{1}{2} + \frac{\theta_0}{2} q - \frac{1}{2} q^2\). On this locus one has \(\tilde{q} = -\frac{\theta_0}{T}\).

Comment. As in Sections 4.4.2 and 4.4.4, the map \(B_1\) is well defined on the reducible loci because \(B_1\) changes the type \((\epsilon_1, \epsilon_2)\) of the reducible loci.

4.4.6 The transformation \(B_2: \theta_0 \mapsto \theta_0, \theta_\infty \mapsto 2 + \theta_\infty, \tilde{t} \mapsto \tilde{t}\)

Let an object of \(\mathcal{M}(\theta_0, \theta_\infty)\) be represented by a standard operator \(z \frac{d}{dz} + A\). We expect that the transformation \(B_2\) yields an object of \(\mathcal{M}(\theta_0, 2 + \theta_\infty)\), represented by a standard operator \(z \frac{d}{dz} + \tilde{A}\). Then \(z \frac{d}{dz} + \tilde{A} = T^{-1}(z \frac{d}{dz} + A)T\) for a certain \(T \in \text{GL}(2, \mathbb{C}(z))\).

Local calculations at \(z = 0\) and \(z = \infty\) show that \(T\) has the form \(T_{-1} z^{-1} + T_0 + T_1 z\) with \(T_{-1} = \begin{pmatrix} 0 & * \\ 0 & 0 \end{pmatrix}\), det \(T_1 = 0\), det \(T \in \mathbb{C}^*\).

The matrix \(A\) depends on \(q\) and \(a := a_{-1}\) and the matrix \(\tilde{A}\) depends on \(\tilde{q}\) and \(\tilde{a} := a_{-1}\). We have to solve the equation \(T(z \frac{d}{dz} + \tilde{A}) = (z \frac{d}{dz} + A)T\).

Maple produced the formula
\[
\tilde{q} = -\frac{(2a + t + \theta_\infty q + tq^2)(2a - t + \theta_\infty q + t q^2)q}{4aq^2 t + 2qt - t^2 - 2q^3 t - q^2 \theta_\infty^2 + 4a^2 - 4aq - 2qt \theta_0 - 2q^2 \theta_\infty + t^2 q^4}.
\]

The denominator of \(\tilde{a}\) is the square of the denominator of \(\tilde{q}\) and the numerator of \(\tilde{a}\) is too large to copy here. The substitution of \(a = \frac{t q - t q}{t^4}\) in the formula for \(\tilde{q}\) yields the \(B_2\) map for the solutions of \(\text{PIII}(D_6)\).

The two cases where \(B_2\) is, \(a\) priori, not defined on the reducible locus are:

1. \((\epsilon_1, \epsilon_2) = (1, 1)\) and \(\frac{\theta_0}{T} = \frac{\theta_\infty}{2} + 1\). The reducible locus is given by \(2a + t + \theta_\infty q + t q^2 = 0\). After substitution of \(\frac{\theta_0}{T} = \frac{\theta_\infty}{2} + 1\), the denominator of \(\tilde{q}\) factors as \((2a + t + \theta_\infty q + t q^2)(2a - t - \theta_\infty q - 2q + t q^2)\). Further \(\tilde{q} = -\frac{(2a + t + \theta_\infty q + t q^2)q}{2a + t - \theta_\infty q - 2q + t q^2}\). On the reducible locus one has \(\tilde{q} = \frac{t q}{t + \theta_\infty q + q}\) and \(B_2\) is well defined.

2. \((\epsilon_1, \epsilon_2) = (-1, 1)\) and \(\frac{\theta_0}{T} = -\frac{\theta_\infty}{2}\). The reducible locus is given by \(2a - t + \theta_\infty q + t q^2 = 0\). After substitution of \(\frac{\theta_0}{T} = -\frac{\theta_\infty}{2}\), the denominator of \(\tilde{q}\) factors as \((2a - t + \theta_\infty q + t q^2)(2a + t - \theta_\infty q - 2q + t q^2)\). Further \(\tilde{q} = -\frac{(2a + t + \theta_\infty q + t q^2)q}{2a + t - \theta_\infty q - 2a + t q^2}\). On the reducible locus one has \(\tilde{q} = \frac{t q}{t - \theta_\infty q - q}\) and \(B_2\) us well defined.

Comment. As in Sections 4.4.2, 4.4.4 and 4.4.5, the map \(B_2\) is well defined because \(B_2\) changes the types \((\epsilon_1, \epsilon_2)\) of the reducible loci.

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References


