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Heun functions and diagonals of rational functions

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Abstract

We provide a set of diagonals of simple rational functions of three and four variables that are squares of Heun functions. These Heun functions obtained through creative telescoping, turn out to be pullbacked ${}_2F_1$ hypergeometric functions that correspond to classical modular forms. We also obtain Heun functions that are associated with Shimura curves as solutions of telescopers of rational functions.

Keywords: diagonals of rational functions, Heun functions, creative telescoping, automorphic forms, modular forms, Shimura curves, pullbacked hypergeometric functions

1. Introduction

Diagonals of rational functions naturally emerge in lattice statistical mechanics, enumerative combinatorics, and more generally, in the context of n -fold integrals of theoretical physics [1, 2]. In previous papers [3, 4, 5] we have seen⁵ that many diagonals of rational functions were pullbacked ${}_2F_1$ hypergeometric functions⁶ that turn out to be related to classical modular forms⁷. Sticking with diagonals of rational functions that are solutions of linear differential operators of *order two*, it is natural to study diagonals of rational functions that are Heun functions.

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⁵ These calculations were performed using the creative telescoping program of Koutschan [6].

⁶ See [7] equation (6) for a definition of a pullback of a hypergeometric function.

⁷ In a sense that we define in appendices A and B.

Heun functions emerge in different areas of physics [1, 8–10] (see also page 60 of [2]) and enumerative combinatorics: the simple cubic lattice Green function [11] can be written as a Heun function, the eigenvalue equation of the Laplace-Beltrami operator on the Eguchi–Hanson space is given by a Heun equation [12, 13]. Heun functions emerging in physics often⁸ correspond to *globally bounded series* [1, 2], i.e. series that can be recast into series with *integer coefficients*. Most of the time they turn out to be pullbacked ${}_2F_1$ hypergeometric functions [14] and in fact *classical modular forms*. In [3] we found diagonals of ‘simple’ rational functions corresponding to classical modular forms when the operator annihilating the diagonal of the rational function had order two. This leads us here to study the class of Heun functions related to classical modular forms that are diagonals of rational functions⁹. We will discard the case where the Heun functions are almost trivial, their linear differential operators of order two factorising into two linear differential operators of order one [15, 16]. In this paper we examine Heun functions, which happen to be either *diagonals of simple rational functions* [2] in three or four variables, or solutions of ‘telescopes’. A telescope is an operator annihilating an n -fold integral *over all possible integration cycles*, including *evanescent integration cycles* which correspond to diagonals of rational functions. More specifically, the ‘telescope’ of a rational function, say $R(x, y, z)$, we refer to here, is the output of the creative telescoping program [6], applied to the *transformed* rational function $\tilde{R} = R(x/y, y/z, z)/(yz)$. Such a telescope is a differential operator T in x, D_x such that $T + D_y \cdot U + D_z \cdot V$ annihilates \tilde{R} , where U, V are rational functions in x, y, z . In other words, the telescope T represents a linear ODE that is satisfied by $Diag(R)$. Now the Heun functions examined in this paper fall into one of three categories:

- (1) Heun functions that are diagonals of rational functions, having *globally bounded series expansions*, and can be rewritten as pullbacked hypergeometric functions that are *classical modular forms*.
- (2) Heun functions that are diagonals of rational functions, having *globally bounded series expansions*, and can be rewritten as pullbacked hypergeometric functions that are *derivatives* of classical modular forms.
- (3) Heun functions that are solutions of *telescopes* of rational functions that have series expansions that are *not* globally bounded and hence cannot be diagonals of rational functions, but are instead solutions of the telescope¹⁰. We show that in this case the Heun functions correspond to *Shimura automorphic forms*.

The Heun function $Heun(a, q, \alpha, \beta, \gamma, \delta, x)$ is solution of the order-two Heun linear differential operator with four singularities (D_x denotes d/dx)

$$H_2 = D_x^2 + \left(\frac{\gamma}{x} + \frac{\delta}{x-1} + \frac{\epsilon}{x-a} \right) \cdot D_x + \frac{\alpha\beta x - q}{x \cdot (x-1) \cdot (x-a)}, \tag{1}$$

where one has the Fuchsian constraint $\epsilon = \alpha + \beta - \gamma - \delta + 1$, where $\alpha, \beta, \gamma, \delta$ need to be rational numbers, and a is an algebraic number. The parameter q is called the *accessory parameter* and the ratio $q/(\alpha\beta)$ is called the *normalised accessory parameter*.

In the first two sections, we examine the Heun functions *emerging from diagonals of simple rational functions* that fall into the first and second category above, and show how they happen to be related to *classical modular forms*, or *derivatives of classical modular forms*,

⁸This is not the case for the Heun functions in [10] which do not correspond to globally bounded series.

⁹Diagonals of rational functions are necessarily globally bounded [1, 2].

¹⁰In this case the diagonal is equal to zero.

corresponding to pullbacked ${}_2F_1$ hypergeometric functions. These Heun functions turn out to be globally bounded. This leads us to define a criterion in appendix A, that allows us to draw a list of parameters of the Gauss hypergeometric function ${}_2F_1([a, b], [c], x)$ that correspond to a *classical modular form* in appendix B. Furthermore, we show in section 2.2 that some of these Heun functions are periods of *extremal rational surfaces*.

In the third section, we examine the solutions of the telescoper of a rational function, corresponding to a Heun function with a series expansion that is *not globally bounded*, and we show that this Heun function is related to a specific *Shimura curve* [17–23].

1.1. Lattice Green functions as diagonals of rational functions

The diagonal of a rational function in n variables $\mathcal{R}(x_1, \dots, x_n) = \mathcal{P}(x_1, \dots, x_n)/\mathcal{Q}(x_1, \dots, x_n)$, where $\mathcal{P}, \mathcal{Q} \in \mathbb{Q}[x_1, \dots, x_n]$ such that $\mathcal{Q}(0, \dots, 0) \neq 0$, is defined through its multi-Taylor expansion around $(0, \dots, 0)$:

$$\mathcal{R}(x_1, \dots, x_n) = \sum_{m_1=0}^{\infty} \cdots \sum_{m_n=0}^{\infty} R_{m_1, \dots, m_n} \cdot x_1^{m_1} \cdots x_n^{m_n}, \tag{2}$$

as the series in *one variable* x :

$$\text{Diag}\left(\mathcal{R}(x_1, \dots, x_n)\right) = \sum_{m=0}^{\infty} R_{m, m, \dots, m} \cdot x^m. \tag{3}$$

With this definition in mind, one can see the simple cubic lattice Green function [24]

$$\frac{1}{(2\pi)^3} \cdot \int_0^{2\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{d\theta_1 d\theta_2 d\theta_3}{1 - x \cdot (\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3))}, \tag{4}$$

as the diagonal of the rational function in four variables x, z_1, z_2, z_3 :

$$\begin{aligned} & \frac{1}{1 - x \cdot z_1 z_2 z_3 \cdot ((1 + z_1^2)/z_1/2 + (1 + z_2^2)/z_2/2 + (1 + z_3^2)/z_3/2)} \\ &= \frac{2}{2 - x \cdot z_1 z_2 z_3 \cdot (z_1 + 1/z_1 + z_2 + 1/z_2 + z_3 + 1/z_3)}, \end{aligned} \tag{5}$$

where the simple lattice Green function is obtained as the diagonal of a four variable rational function through the following substitution: $\cos(\theta_i) = (1 + z_i^2)/2/z_i$, i.e. $z_i = \exp(i\theta_i)$, and $x \rightarrow x \cdot z_1 z_2 z_3$.

The linear differential operator annihilating the diagonal (5), has order three. This operator is the *symmetric square*¹¹ of a linear differential operator of order two where θ is the homogeneous derivative $x \cdot d/dx$:

$$9x^4 \cdot (2\theta + 3) \cdot (2\theta + 1) - 4x^2 \cdot (10\theta^2 + 10\theta + 3) + 4\theta^2, \tag{6}$$

whose solution is given by a Heun function. Hence, we see that the diagonal of (5) reads:

$$\text{Heun}\left(\frac{1}{9}, \frac{1}{12}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, x^2\right)^2 \quad \text{or} \quad \text{Heun}\left(9, \frac{3}{4}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, 9x^2\right)^2. \tag{7}$$

¹¹ The symmetric power of an operator L is the minimal operator M such that for every set of m solutions y_1, \dots, y_m of L , the product $y_1 y_2 \dots y_m$ is a solution of M . In particular, the symmetric square of an operator L is the symmetric power of the operator L with $m = 2$.

The Heun function on the right in (7) happens to be a period of an *extremal rational curve* as can be seen in the work of Doran and Malmendier [25]. These Heun functions¹² in (7) can be rewritten as pullbacked ${}_2F_1$ hypergeometric functions that correspond to *classical modular forms* as can be seen in example 1 in section 2.1 below¹³.

2. Diagonals of rational functions in three and four variables, corresponding to Heun functions related to classical modular forms

In the previous section we have mentioned that the rational function whose diagonal is given by the simple cubic lattice is related to modular forms. We will begin by showing this link explicitly in Example 1. In the five other examples we give different rational functions in four variables, some of whom can be found in [27], whose diagonal is given by Heun functions that can be rewritten in terms of Gauss hypergeometric functions related to modular forms. As the reader might guess, the problem of finding rational functions in four variables, whose diagonal is given by Heun functions that can be rewritten in terms of modular forms, is not an easy task!

2.1. Diagonals of rational functions corresponding to Heun functions

- Example 1. Let us consider the following rational function in four variables x, y, z and w

$$R(x, y, z, w) = \frac{1}{1 - (y + z + wy + xz + wxy + wxz)}, \tag{8}$$

or the rational function:

$$R(x, y, z, w) = \frac{1}{1 + xy + yz + zw + wx + yw + xz}. \tag{9}$$

The diagonals of these two rational functions (8) and (9) have the *same* series expansion with integer coefficients:

$$\begin{aligned} \text{Diag}(R(x, y, z, w)) = & 1 + 6x + 90x^2 + 1860x^3 + 44730x^4 + 1172556x^5 \\ & + 32496156x^6 + 936369720x^7 + \dots \end{aligned} \tag{10}$$

The linear differential operator of order three annihilating the series (10) is the *symmetric square* of a linear differential operator of order two. The diagonal (10), solution of this order-three operator, can be written as:

$$\text{Heun}\left(\frac{1}{9}, \frac{1}{12}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, 4x\right)^2 = (1 - 4x) \cdot \text{Heun}\left(\frac{1}{9}, \frac{5}{36}, \frac{3}{4}, \frac{5}{4}, 1, \frac{3}{2}, 4x\right)^2. \tag{11}$$

¹² These Heun functions can be alternatively written as $\text{Heun}\left(\frac{1}{9}, \frac{1}{3}, 1, 1, 1, x\right)$. See appendix A equation (A.12) in [2] for more details.

¹³ An example of emergence of modular functions in the context of K3 surfaces through Dedekind’s η -functions can be found in section 4 of [26].

The Heun function (11) can be written as a pullbacked ${}_2F_1$ hypergeometric function

$$\begin{aligned} Heun\left(\frac{1}{9}, \frac{1}{12}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, 4x\right) \\ = \mathcal{A}_{\pm}^{(1)} \cdot {}_2F_1\left(\left[\frac{1}{6}, \frac{2}{3}\right], [1], \mathcal{H}_{\pm}^{(1)}\right) = \mathcal{A}_{\pm}^{(2)} \cdot {}_2F_1\left(\left[\frac{1}{8}, \frac{5}{8}\right], [1], \mathcal{H}_{\pm}^{(2)}\right), \end{aligned} \tag{12}$$

where the two pullbacks $\mathcal{H}_{\pm}^{(1)}, \mathcal{H}_{\pm}^{(2)}$ are square root algebraic functions

$$\begin{aligned} \mathcal{H}_{\pm}^{(1)} = -54 \cdot x \cdot \frac{1 - 27x - 108x^2}{(1 - 54x)^2} \\ \pm 54 \cdot x \cdot (1 - 9x) \cdot \frac{(1 - 4x)^{1/2} \cdot (1 - 36x)^{1/2}}{(1 - 54x)^2}, \end{aligned} \tag{13}$$

$$\begin{aligned} \mathcal{H}_{\pm}^{(2)} = -128 \cdot x \cdot \frac{1 - 38x + 200x^2}{(1 - 100x)^2 \cdot (1 - 4x)} \\ \pm 128 \cdot x \cdot (1 - 20x) \cdot \frac{(1 - 36x)^{1/2}}{(1 - 100x)^2 \cdot (1 - 4x)}, \end{aligned} \tag{14}$$

where $Y_{\pm} = (\mathcal{A}_{\pm}^{(1)})^{12}$ are simple algebraic functions, respectively solutions of

$$64 + p_3(x) \cdot Y_+ + (1 - 54x)^4 \cdot Y_+^2 = 0, \tag{15}$$

$$1 + p_3(x) \cdot Y_- + 64 \cdot (1 - 54x)^4 \cdot Y_-^2 = 0, \tag{16}$$

where

$$p_3(x) = 186\,624x^3 - 15\,552x^2 + 2484x - 65, \tag{17}$$

and where $Y_{\pm} = (\mathcal{A}_{\pm}^{(2)})^8$ are simple algebraic functions, respectively solutions of

$$81 - 2 \cdot (41 - 900x) \cdot (1 - 4x) \cdot Y_+ + (1 - 100x)^2 \cdot (1 - 4x)^2 \cdot Y_+^2 = 0, \tag{18}$$

$$1 - 2 \cdot (41 - 900x) \cdot (1 - 4x) \cdot Y_- + 81 \cdot (1 - 100x)^2 \cdot (1 - 4x)^2 \cdot Y_-^2 = 0. \tag{19}$$

The two Hauptmoduls $\mathcal{H}_{\pm}^{(1)}$ have the following series expansions

$$\begin{aligned} \mathcal{H}_{-}^{(1)} = -108x - 8640x^2 - 615\,168x^3 - 41\,167\,872x^4 - 2650\,337\,280x^5 \\ - 166\,137\,937\,920x^6 - 10\,213\,026\,103\,296x^7 - 618\,505\,440\,067\,584x^8 + \dots \end{aligned} \tag{20}$$

and

$$\begin{aligned} \mathcal{H}_{+}^{(1)} = -108x^2 - 3024x^3 - 87\,696x^4 - 2616\,192x^5 - 79\,800\,768x^6 \\ - 2477\,350\,656x^7 - 78\,006\,945\,024x^8 - 2485\,113\,716\,736x^9 + \dots \end{aligned} \tag{21}$$

and are related by the *genus zero* modular equation:

$$\begin{aligned} 625A^3B^3 - 525A^2B^2 \cdot (A+B) - 96AB \cdot (A^2+B^2) - 3A^2B^2 \\ - 4 \cdot (A^3+B^3) + 528 \cdot AB \cdot (A+B) - 432 \cdot AB = 0. \end{aligned} \tag{22}$$

- Example 2. The diagonal of the rational function

$$R(x, y, z, w) = \frac{1}{1 - (wx + yz + wxy + wxz + wyz + xyz)}, \quad (23)$$

reads:

$$Diag(R(x, y, z, w)) = 1 + 2x + 18x^2 + 164x^3 + 1810x^4 + \dots \quad (24)$$

The linear differential operator annihilating the diagonal (24) of the rational function (23) has order three:

$$L_3 = 2 + 60x - (1 - 40x - 444x^2) \cdot D_x - 3x \cdot (1 - 18x - 128x^2) \cdot D_x^2 - x^2 \cdot (1 + 4x) \cdot (1 - 16x) \cdot D_x^3. \quad (25)$$

The operator (25) is the *symmetric square* of a linear differential operator of order two. Hence the solution corresponding to the diagonal of (23) is given by the square of a Heun function:

$$\begin{aligned} Heun\left(-\frac{1}{4}, \frac{1}{16}, \frac{3}{8}, \frac{5}{8}, 1, \frac{1}{2}, -4x\right)^2 \\ = 1 + 2x + 18x^2 + 164x^3 + 1810x^4 + 21252x^5 + 263844x^6 \\ + 3395016x^7 + 44916498x^8 + \dots \end{aligned} \quad (26)$$

This Heun function can be written as a pullbacked ${}_2F_1$ hypergeometric function:

$$Heun\left(-\frac{1}{4}, \frac{1}{16}, \frac{3}{8}, \frac{5}{8}, 1, \frac{1}{2}, -4x\right) = \mathcal{A}_\pm \cdot {}_2F_1\left(\left[\frac{1}{8}, \frac{3}{8}\right], [1], \mathcal{H}_\pm\right), \quad (27)$$

where \mathcal{A}_\pm and the Hauptmodul \mathcal{H}_\pm are algebraic functions expressed with square roots:

$$\begin{aligned} \mathcal{H}_\pm = -128x \cdot \frac{1 - 20x + 50x^2 + 400x^3 - 224x^4 - 512x^5}{(1 - 88x - 112x^2 - 256x^3)^2} \\ \pm 128x \cdot \frac{(1 + 2x)(1 - 12x)(1 - 4x) \cdot (1 + 4x)^{1/2} \cdot (1 - 16x)^{1/2}}{(1 - 88x - 112x^2 - 256x^3)^2}. \end{aligned} \quad (28)$$

These Hauptmoduls (28) are also given by the quadratic relation having *genus zero*:

$$\begin{aligned} (256x^3 + 112x^2 + 88x - 1)^2 \cdot \mathcal{H}_\pm^2 \\ - 256 \cdot x \cdot (512x^5 + 224x^4 - 400x^3 - 50x^2 + 20x - 1) \cdot \mathcal{H}_\pm \\ + 65536x^6 = 0, \end{aligned} \quad (29)$$

and have the series expansions:

$$\begin{aligned} \mathcal{H}_- = -256x - 39936x^2 - 5116416x^3 - 595357696x^4 - 65525931776x^5 \\ - 6954923846656x^6 - 719583708750336x^7 + \dots \\ \mathcal{H}_+ = -256x^5 - 5120x^6 - 89600x^7 - 1433600x^8 - 22201600x^9 \\ - 337755136x^{10} - 5094679040x^{11} + \dots \end{aligned} \quad (30)$$

The relation between these two Hauptmoduls corresponds to a genus zero $q \leftrightarrow q^5$ modular equation (q denotes the nome of the operator of order two).

- Example 3. The rational function in four variables:

$$R(x, y, z, w) = \frac{1}{1 - (y + z + xy + xz + wxy + wxz + wyz)}, \quad (31)$$

has a diagonal that reads:

$$\begin{aligned} \text{Diag}(R(x, y, z, w)) = & 1 + 4x + 48x^2 + 760x^3 + 13\,840x^4 + 273\,504x^5 \\ & + 5703\,096x^6 + 123\,519\,792x^7 + \dots \end{aligned} \quad (32)$$

The linear differential operator annihilating the diagonal of this rational function is the following linear differential operator of order three, which is the *symmetric square* of an operator of order two:

$$\begin{aligned} x^2 \cdot (1 + x) \cdot (1 - 27x) \cdot D_x^3 & + 3x \cdot (1 - 39x - 54x^2) \cdot D_x^2 \\ & + (1 - 86x - 186x^2) \cdot D_x - 4 \cdot (1 + 6x). \end{aligned} \quad (33)$$

The operator (33) admits a Heun function that has series expansion with integer coefficients as a solution:

$$\begin{aligned} \text{Heun}\left(-\frac{1}{27}, \frac{2}{27}, \frac{1}{3}, \frac{2}{3}, 1, \frac{1}{2}, -x\right)^2 = & 1 + 4x + 48x^2 + 760x^3 + 13\,840x^4 \\ & + 273\,504x^5 + 5703\,096x^6 + 123\,519\,792x^7 + \dots \end{aligned} \quad (34)$$

We also have the following series expansion with integer coefficients:

$$\begin{aligned} \text{Heun}\left(-\frac{1}{27}, \frac{2}{27}, \frac{1}{3}, \frac{2}{3}, 1, \frac{1}{2}, -x\right) = & 1 + 2x + 22x^2 + 336x^3 + 6006x^4 \\ & + 117\,348x^5 + 2428\,272x^6 + 52\,303\,680x^7 + \dots \end{aligned} \quad (35)$$

The Heun function (35) can be written as a pullbacked ${}_2F_1$ hypergeometric function

$$\begin{aligned} \text{Heun}\left(-\frac{1}{27}, \frac{2}{27}, \frac{1}{3}, \frac{2}{3}, 1, \frac{1}{2}, -x\right) = & \\ (25 - 80x - 24 \cdot (1 + x)^{1/2} \cdot (1 - 27x)^{1/2})^{-1/4} \cdot & {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], \mathcal{H}_+\right), \end{aligned} \quad (36)$$

where the Hauptmodul \mathcal{H} reads:

$$\begin{aligned} \mathcal{H}_\pm = & 864 \cdot x \cdot \frac{(1 - 21x + 8x^2) \cdot (1 - 42x + 454x^2 - 1008x^3 - 1280x^4)}{(1 + 224x + 448x^2)^3} \\ & \pm 864 \cdot x \cdot (1 - 8x) \cdot (1 - 2x) \cdot (1 - 24x) \cdot (1 - 16x - 8x^2) \\ & \times \frac{(1 + x)^{1/2} \cdot (1 - 27x)^{1/2}}{(1 + 224x + 448x^2)^3}. \end{aligned} \quad (37)$$

The series expansions of these two Hauptmoduls (37) read respectively

$$\begin{aligned} \mathcal{H}_+ = & 1728x - 1270\,080x^2 + 593\,381\,376x^3 - 226\,343\,666\,304x^4 \\ & + 76\,907\,095\,308\,288x^5 - 24\,246\,668\,175\,851\,520x^6 + \dots \end{aligned} \quad (38)$$

and:

$$\begin{aligned} \mathcal{H}_- = & 1728x^7 + 108\,864x^8 + 4536\,000x^9 + 158\,251\,968x^{10} \\ & + 5017\,070\,016x^{11} + 150\,134\,378\,688x^{12} + 4328\,271\,255\,168x^{13} + \dots \end{aligned} \quad (39)$$

These two Hauptmoduls are the two solutions of the *quadratic* genus zero relation:

$$1728^2 \cdot x^8 + 1728 \cdot (1 - 21x + 8x^2)(1280x^4 + 1008x^3 - 454x^2 + 42x - 1) \cdot x \cdot \mathcal{H}_\pm + (1 + 224x + 448x^2)^3 \cdot \mathcal{H}_\pm^2 = 0, \tag{40}$$

and the two j -invariants ($\mathcal{H}_\pm = 1728/j_\pm$) are solutions of the quadratic relation:

$$x^8 \cdot j_\pm^2 + (1 - 21x + 8x^2)(1280x^4 + 1008x^3 - 454x^2 + 42x - 1) \cdot x \cdot j_\pm + (1 + 224x + 448x^2)^3 = 0. \tag{41}$$

Denoting $A = \mathcal{H}_+$ and $B = \mathcal{H}_-$ and considering the two (identical) quadratic relations (40) $Q(x, A) = 0$ and $Q(x, B) = 0$, one easily gets by performing the resultant between $Q(x, A) = 0$ and $Q(x, B) = 0$ in x , and thus eliminating x , the *modular equation* $P(A, B) = 0$. One gets a large *modular equation* of *genus zero* corresponding to $q \leftrightarrow q^7$ in the nome q (see (38) and (39)):

$$81 \cdot 600^9 \cdot A^6 B^6 \cdot (343A^2 + 286AB + 343B^2) + \dots - 2^{36} \cdot 3^{18} \cdot AB = 0. \tag{42}$$

Now the previous Heun function can be written with a different algebraic Hauptmodul H and a different algebraic function \mathcal{A} :

$$\text{Heun}\left(-\frac{1}{27}, \frac{2}{27}, \frac{1}{3}, \frac{2}{3}, 1, \frac{1}{2}, -x\right) = \mathcal{A} \cdot {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], H\right), \tag{43}$$

where this Hauptmodul is solution of the degree six equation:

$$p_6(x)^3 \cdot (1 - 2x)^6 \cdot H^6 + 3 \cdot 1728 \cdot x^4 \cdot p_{20}(x) \cdot (1 - 2x)^3 \cdot H^5 - 1728^2 \cdot x \cdot p_{23}(x) \cdot H^4 + 1728^3 \cdot x^3 \cdot p_{21}(x) \cdot H^3 + 1728^4 \cdot x^8 \cdot p_{16}(x) \cdot H^2 - 1728^5 \cdot x^{10} \cdot p_{14}(x) \cdot H + 1728^6 \cdot x^{24} = 0, \tag{44}$$

where the polynomials $p_n(x)$ are polynomials of degree n . Note that the curve (44) is a *genus one* curve. This degree six polynomial equation (44) in H , gives Hauptmoduls having the following series expansions:

$$1728x^2 + 31\,104x^3 - 689\,472x^4 - 34\,193\,664x^5 - 431\,329\,536x^6 + \dots \tag{45}$$

and

$$1728x^{14} + 217\,728x^{15} + 15\,930\,432x^{16} + 888\,039\,936x^{17} + \dots \tag{46}$$

corresponding to $q \leftrightarrow q^7$ in the nome q . By denoting A and B two Hauptmoduls solutions of degree six of (44), $Q_6(x, A) = 0$ and $Q_6(x, B) = 0$, one gets by elimination of x through a resultant of $Q_6(x, A)$ and $Q_6(x, B)$ in x , the modular equation $P(A, B) = 0$. Now this *modular curve* is also a *genus one* curve.

- Example 4. The rational function in four variables

$$R(x, y, z, w) = \frac{1}{1 - (y + z + wz + xy + xz + wxy)}, \tag{47}$$

has a diagonal whose series expansion reads:

$$\text{Diag}\left(R(x, y, z, w)\right) = 1 + 4x + 60x^2 + 1120x^3 + 24\,220x^4 + 567\,504x^5 + 14\,030\,016x^6 + 360\,222\,720x^7 + \dots \tag{48}$$

The linear differential operator annihilating the diagonal of this rational function (47) has order three:

$$4 + 96 \cdot x - (1 - 92 \cdot x - 864 \cdot x^2) \cdot D_x - 3x \cdot (1 - 42 \cdot x - 256 \cdot x^2) \cdot D_x^2 - x^2 \cdot (1 + 4x) \cdot (1 - 32x) \cdot D_x^3. \tag{49}$$

This order-three linear differential operator is the *symmetric square* of a linear differential operator of order two, admitting as solution the square of a Heun function, which has a series expansion with integer coefficients:

$$Heun\left(-\frac{1}{8}, \frac{1}{16}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, -4x\right)^2 = 1 + 4x + 60x^2 + 1120x^3 + 24220x^4 + 567504x^5 + \dots, \tag{50}$$

which is related to the Heun function of example 1 through the following relation:

$$Heun\left(-\frac{1}{8}, \frac{1}{16}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, -4x\right)^2 = (1 + 4x)^{-1/2} \cdot Heun\left(\frac{1}{9}, \frac{1}{12}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, \frac{4x}{1 + 4x}\right)^2. \tag{51}$$

The linear differential operator (49) is the *symmetric square* of a linear differential operator of order two having a pullbacked ${}_2F_1$ hypergeometric function as a solution:

$$Heun\left(-\frac{1}{8}, \frac{1}{16}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, -4x\right) = 1 + 2x + 28x^2 + 504x^3 + 10710x^4 + 248220x^5 + 6091680x^6 + 155580000x^7 + 4092325500x^8 + \dots = \mathcal{A}_{\pm}^{(1)} \cdot {}_2F_1\left(\left[\frac{1}{6}, \frac{2}{3}\right], [1], \mathcal{H}_{\pm}^{(1)}\right) = \mathcal{A}_{\pm}^{(2)} \cdot {}_2F_1\left(\left[\frac{1}{8}, \frac{5}{8}\right], [1], \mathcal{H}_{\pm}^{(2)}\right), \tag{52}$$

where $\mathcal{A}_{\pm}^{(1)}$, $\mathcal{A}_{\pm}^{(2)}$ and the two Hauptmoduls $\mathcal{H}_{\pm}^{(1)}$ are square root algebraic functions:

$$\mathcal{H}_{\pm}^{(1)} = -54x \cdot \frac{1 - 19x - 200x^2}{(1 + 4x) \cdot (1 - 50x)^2} \pm 54 \cdot x \cdot (1 - 32x)^{1/2} \cdot \frac{1 - 5x}{(1 + 4x) \cdot (1 - 50x)^2}. \tag{53}$$

The two Hauptmoduls $\mathcal{H}_{\pm}^{(1)}$ are solutions of the quadratic relation:

$$(1 + 4x) \cdot (1 - 50x)^2 \cdot (\mathcal{H}_{\pm}^{(1)})^2 - 108x \cdot (200x^2 + 19x - 1) \cdot \mathcal{H}_{\pm}^{(1)} + 11664x^3 = 0. \tag{54}$$

The two Hauptmoduls $\mathcal{H}_{\pm}^{(2)}$ in (52) are also square root algebraic functions:

$$\mathcal{H}_{\pm}^{(2)} = -28 \cdot x \cdot \frac{1 - 30x + 64x^2}{(1 - 96x)^2} \pm 28 \cdot x \cdot (1 - 16x) \cdot \frac{(1 + 4x)^{1/2} \cdot (1 - 32x)^{1/2}}{(1 - 96x)^2}, \tag{55}$$

which are solutions of the quadratic relation

$$(1 - 96x)^2 \cdot (\mathcal{H}_{\pm}^{(2)})^2 + 256x \cdot (64x^2 - 30x + 1) \cdot \mathcal{H}_{\pm}^{(2)} + 65\,536x^4 = 0, \tag{56}$$

the algebraic function $\mathcal{A}_{\pm}^{(1)}$ being solution of

$$512 - 27 \cdot (1 - 20x) \cdot (19 - 312x - 6000x^2 - 80\,000x^3) \cdot Y + (1 + 4x)^3 \cdot (1 - 50x)^6 \cdot Y^2 = 0, \tag{57}$$

where $Y = (\mathcal{A}_{\pm}^{(1)})^{18}$, and the algebraic function $\mathcal{A}_{\pm}^{(2)}$ being solution of

$$1 + 2 \cdot q_8(x) \cdot Y + 3^{32} \cdot (1 - 96x)^{16} \cdot Y^2 = 0, \quad \text{where:} \tag{58}$$

$$\begin{aligned} q_8(x) = & 92\,393\,273\,930\,231\,100\,473\,344x^8 - 182\,396\,792\,383\,587\,915\,661\,312x^7 \\ & + 7442\,201\,965\,961\,886\,564\,352x^6 + 10\,564\,527\,655\,702\,470\,066\,176x^5 \\ & - 1994\,146\,206\,485\,388\,984\,320x^4 + 154\,408\,466\,296\,830\,427\,136x^3 \\ & - 6048\,257\,896\,412\,868\,608x^2 + 118\,593\,292\,086\,518\,528x - 926\,510\,094\,425\,921, \end{aligned} \tag{59}$$

where $Y = (\mathcal{A}_{\pm}^{(2)})^{64}$. The series expansions of the Hauptmoduls $\mathcal{H}_{\pm}^{(1)}$ read:

$$\begin{aligned} \mathcal{H}_{-}^{(1)} = & -108x - 8208x^2 - 547\,776x^3 - 34\,193\,664x^4 - 2048\,523\,264x^5 \\ & - 119\,335\,292\,928x^6 - 6811\,411\,267\,584x^7 - 382\,782\,182\,326\,272x^8 + \dots \end{aligned} \tag{60}$$

and:

$$\begin{aligned} \mathcal{H}_{+}^{(1)} = & -108x^2 - 2160x^3 - 56\,592x^4 - 1475\,712x^5 - 39\,711\,168x^6 \\ & - 1088\,716\,032x^7 - 30\,317\,739\,264x^8 - 854\,924\,599\,296x^9 + \dots \end{aligned} \tag{61}$$

The relation between these two Hauptmoduls corresponds to the genus zero *modular equation*:

$$\begin{aligned} 625 A^3 B^3 - 525 A^2 B^2 \cdot (A + B) - 96 A B \cdot (A^2 + B^2) - 3 A^2 B^2 \\ - 4 \cdot (A^3 + B^3) + 528 \cdot A B \cdot (A + B) - 432 \cdot A B = 0, \end{aligned} \tag{62}$$

which can (for instance) be rationally parametrised as follows:

$$A(v) = \frac{108 \cdot v \cdot (1 + v)^2}{(16 + 15v) \cdot (2 + 3v)^2}, \quad B(v) = -\frac{108 \cdot (1 + v) \cdot v^2}{(4 + 3v) \cdot (32 + 33v)^2}, \tag{63}$$

where $A(v)$ and $B(v)$ are related by an involution:

$$B(v) = A\left(-\frac{64 \cdot (1 + v)}{63v + 64}\right), \quad A(v) = B\left(-\frac{64 \cdot (1 + v)}{63v + 64}\right). \tag{64}$$

The series expansions of the Hauptmoduls $\mathcal{H}_{\pm}^{(2)}$ read:

$$\begin{aligned} \mathcal{H}_{-}^{(2)} = & -56x - 9072x^2 - 1229\,256x^3 - 152\,418\,672x^4 - 17\,935\,321\,320x^5 \\ & - 2038\,883\,437\,584x^6 - 226\,173\,478\,925\,520x^7 + \dots \end{aligned} \tag{65}$$

and

$$\mathcal{H}_+^{(2)} = -56x^3 - 1680x^4 - 46872x^5 - 1291248x^6 - 35752752x^7 - 998627616x^8 - 28151491032x^9 - 800518405680x^{10} + \dots \quad (66)$$

The relation between these last two Hauptmoduls $\mathcal{H}_\pm^{(2)}$ corresponds to a genus zero modular equation:

$$\begin{aligned} &640000 \cdot A^2 B^2 \cdot (9A^2 + 14AB + 9B^2) \\ &+ 4800AB \cdot (A + B) \cdot (A^2 - 1954AB + B^2) \\ &+ A^4 + B^4 - 56196AB \cdot (A^2 + B^2) + 3512070A^2 B^2 \\ &+ 116736 \cdot AB \cdot (A + B) - 65536 \cdot AB = 0, \end{aligned} \quad (67)$$

which is the same modular equation as (62). Now the modular equation (22) of example 1, is actually the same as the modular equation (67) of example 4! This is a consequence of identity (51).

- Example 5. The rational function in four variables

$$R(x, y, z, w) = \frac{1}{1 - (y + z + xy + xz + wy + wz + wxz)}, \quad (68)$$

has a diagonal that reads:

$$Diag(R(x, y, z, w)) = 1 + 6x + 114x^2 + 2940x^3 + 87570x^4 + \dots \quad (69)$$

The operator annihilating the diagonal (69) of this rational function in four variables (68) reads:

$$\begin{aligned} &6 + 12 \cdot x - (1 - 144 \cdot x - 108 \cdot x^2) \cdot D_x - x \cdot (3 - 198 \cdot x - 96 \cdot x^2) \cdot D_x^2 \\ &- x^2 \cdot (1 - 44 \cdot x - 16 \cdot x^2) \cdot D_x^3. \end{aligned} \quad (70)$$

It is the symmetric square of a linear differential operator of order two which admits a Heun solution analytic at $x = 0$. Consequently the rational function of order three (70) has a solution that is the square of a Heun function, and admits the series expansion with integer coefficients:

$$\begin{aligned} &Heun\left(-\frac{123}{2} + \frac{55}{2} \cdot 5^{1/2}, -\frac{33}{8} + \frac{15}{8} \cdot 5^{1/2}, \frac{1}{4}, \frac{3}{4}, 1, \frac{1}{2}, 2 \cdot (11 - 5 \cdot 5^{1/2}) \cdot x\right)^2 \\ &= 1 + 6x + 114x^2 + 2940x^3 + 87570x^4 + 2835756x^5 + 96982116x^6 \\ &+ 3446781624x^7 + 126047377170x^8 + \dots \end{aligned} \quad (71)$$

The Heun solution (71) can also be rewritten as a pullbacked ${}_2F_1$ hypergeometric function:

$$\mathcal{A}(x) \cdot {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], \mathcal{H}\right)^2, \quad (72)$$

where $\mathcal{A}(x)$ is an algebraic function and where the Hauptmodul \mathcal{H} is solution of the quadratic relation:

$$\begin{aligned} &(144x^2 + 216x + 1)^3 \cdot \mathcal{H}^2 \\ &- 1728x \cdot (3456x^5 + 7776x^4 - 12600x^3 + 1890x^2 - 80x + 1) \cdot \mathcal{H} \\ &+ 2985984x^6 = 0. \end{aligned} \quad (73)$$

The two Hauptmoduls read

$$\begin{aligned} \mathcal{H}_{\pm} &= \frac{864x \cdot (3456x^5 + 7776x^4 - 12600x^3 + 1890x^2 - 80x + 1)}{(144x^2 + 216x + 1)^3} \\ &\pm \frac{864(1 - 36x) \cdot (1 - 18x)(1 - 4x)x}{(144x^2 + 216x + 1)^3} \cdot (1 - 44x - 16x^2)^{1/2}, \end{aligned} \quad (74)$$

and admit the respective expansions:

$$\begin{aligned} \mathcal{H}_+ &= 1728x - 1257984x^2 + 575828352x^3 - 214274336256x^4 + \dots \\ \mathcal{H}_- &= 1728x^5 + 138240x^6 + 7793280x^7 + 383961600x^8 + \dots \end{aligned} \quad (75)$$

These two Hauptmoduls series (74) are related by a *genus zero* modular equation which admits the following rational parametrization¹⁴ as:

$$\mathcal{H}_+ = \frac{1728z}{(z^2 + 10z + 5)^3}, \quad \mathcal{H}_- = \frac{1728z^5}{(z^2 + 250z + 3125)^3}. \quad (76)$$

- Example 6. The rational function in four variables

$$R(x, y, z, w) = \frac{1}{1 - (y + z + xy + xz + wz + wxy + wxyz)}, \quad (77)$$

has a diagonal that reads:

$$Diag(R(x, y, z, w)) = 1 + 5x + 73x^2 + 1445x^3 + 33001x^4 + \dots \quad (78)$$

The operator annihilating the diagonal of the rational function (77) reads:

$$\begin{aligned} L_3 &= x^2 \cdot (1 - 34x + x^2) \cdot D_x^3 + 3x \cdot (1 - 51x + 2x^2) \cdot D_x^2 \\ &+ (1 - 112x + 7x^2) \cdot D_x + x - 5. \end{aligned} \quad (79)$$

It is the *symmetric square* of an order-two linear differential operator with a Heun solution, analytic at $x = 0$. Consequently the diagonal of (77), solution of (79), can be written in terms of the square of two Heun functions¹⁵ which have series expansions with integer coefficients:

$$\begin{aligned} &(1 - 34x + x^2) \\ &\times Heun\left(577 + 408 \cdot 2^{1/2}, \frac{663}{2} + 234 \cdot 2^{1/2}, \frac{3}{2}, \frac{3}{2}, 1, \frac{3}{2}, (17 + 12 \cdot 2^{1/2}) \cdot x\right)^2 \\ = &(1 - 34x + x^2) \\ &\times Heun\left(577 - 408 \cdot 2^{1/2}, \frac{663}{2} - 234 \cdot 2^{1/2}, \frac{3}{2}, \frac{3}{2}, 1, \frac{3}{2}, (17 - 12 \cdot 2^{1/2}) \cdot x\right)^2 \\ = &1 + 5x + 73x^2 + 1445x^3 + 33001x^4 + 819005x^5 + 21460825x^6 + \dots \end{aligned} \quad (80)$$

It can also be written as a pullbacked ${}_2F_1$ hypergeometric function

$$\mathcal{A}_- \cdot {}_2F_1\left(\left[\frac{1}{3}, \frac{2}{3}\right], [1], \mathcal{H}_-\right)^2, \quad (81)$$

¹⁴ It corresponds to $N = 5$ in tables 4 and 5 of [28].

¹⁵ These two Heun functions are Galois conjugates.

where the Hauptmodul \mathcal{H}_\pm reads

$$\mathcal{H}_\pm = \frac{1 - 24x + 30x^2 + x^3}{2 \cdot (1 + x)^3} \pm \frac{1 - 7x + x^2}{2 \cdot (1 + x)^3} \cdot (1 - 34x + x^2)^{1/2}, \tag{82}$$

with the expansions:

$$\begin{aligned} \mathcal{H}_- = & 27x^2 + 648x^3 + 15471x^4 + 389016x^5 + 10234107x^6 + 278861616x^7 \\ & + 7808397759x^8 + 223397228880x^9 + \dots \end{aligned} \tag{83}$$

and where the algebraic factor \mathcal{A}_- reads:

$$\mathcal{A}_- = \frac{3}{2} \cdot \frac{1 - x}{(1 + x)^2} - \frac{(1 - 34x + x^2)^{1/2}}{2 \cdot (1 + x)^2}. \tag{84}$$

2.2. Periods of extremal rational surfaces

The rational function in *three* variables:

$$R(x, y, z) = \frac{1}{1 + x + y + z + xy + yz - x^3yz}, \tag{85}$$

has a diagonal given by the following series expansion:

$$\begin{aligned} \text{Diag}(R(x, y, z)) = & 1 - 2x + 6x^2 - 11x^3 - 10x^4 + 273x^5 - 1875x^6 \\ & + 9210x^7 - 34218x^8 + 78721x^9 + 108581x^{10} + \dots \end{aligned} \tag{86}$$

In order to find the diagonal of this rational function of three variables, one gets the telescoper annihilating this diagonal using creative telescoping [6]. This telescoper is a linear differential operator of order four L_4 , which is the *direct sum* of two¹⁶ linear differential operators having order two $L_4 = L_2 \oplus M_2$. These two operators read respectively

$$L_2 = (1 + 9x + 27x^2) \cdot x^2 \cdot D_x^2 + (1 + 9x)^2 \cdot x \cdot D_x + 3x \cdot (1 + 9x),$$

and:

$$\begin{aligned} M_2 = & (1 + 9x + 27x^2) \cdot (5 + 18x) \cdot (1 - 2x) \cdot x^2 \cdot D_x^2 \\ & + (5 + 70x + 261x^2 - 756x^3 - 2916x^4) \cdot x \cdot D_x \\ & + x \cdot (1 - 9x) \cdot (5 + 60x + 108x^2). \end{aligned} \tag{87}$$

The solution of the order-two linear differential operator L_2 has the following Heun function¹⁷ solution, analytic at $x = 0$:

$$\mathcal{S}_1 = \text{Heun}\left(\frac{1}{2} - \frac{i\sqrt{3}}{2}, \frac{1}{2} - \frac{i\sqrt{3}}{6}, 1, 1, 1, 1, \frac{3}{2} \cdot (-3 + i\sqrt{3}) \cdot x\right) \tag{88}$$

¹⁶ These two operators L_2 and M_2 are not homomorphic because they do not have the same singularities.

¹⁷ This Heun function $\text{Heun}(a, q, \alpha, \beta, \gamma, \delta, \rho x)$ is such that $q = a/(1 + a)$, $q/\rho = -1/9$, $a/\rho^2 = 1/27$, $1/\rho$ and a/ρ are complex conjugates.

$$= 1 - 3x + 9x^2 - 21x^3 + 9x^4 + 297x^5 - 2421x^6 + 12933x^7 + \dots \quad (89)$$

This Heun function (88) can also be written alternatively in terms of other ${}_2F_1$ hypergeometric functions:

$$\begin{aligned} Heun\left(\frac{1}{2} - \frac{i\sqrt{3}}{2}, \frac{1}{2} - \frac{i\sqrt{3}}{6}, 1, 1, 1, 1, \frac{3}{2} \cdot (-3 + i\sqrt{3}) \cdot x\right) \\ = \left(\frac{1}{1+3x}\right)^{1/4} \cdot \left(\frac{1}{1+9x+27x^2+3x^3}\right)^{1/4} \\ \times {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], \frac{1728 \cdot x^9 \cdot (1+9x+27x^2)}{(1+3x)^3 \cdot (1+9x+27x^2+3x^3)^3}\right) \\ = (1+9x)^{-1/4} \cdot (1+243x+2187x^2+6561x^3)^{-1/4} \\ \times {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], \frac{1728 \cdot x \cdot (1+9x+27x^2)}{(1+9x)^3 \cdot (1+243x+2187x^2+6561x^3)^3}\right). \end{aligned} \quad (90)$$

The modular equation relating the Hauptmoduls of the two Gauss hypergeometric functions in (91) corresponds to $q \leftrightarrow q^9$ in the nome q (see also tables 4 and 5 in [28]).

The Heun function (90) is in fact the *period* of an *extremal rational surface* [25], and was shown to be related¹⁸ to *classical modular forms* in table 15 in [28] for $N = 9$:

$$\begin{aligned} Heun\left(\frac{-9 \mp 3\sqrt{3}i}{-9 \pm 3\sqrt{3}i}, \frac{9 \pm 3\sqrt{3}i}{18}, 1, 1, 1, 1, \frac{2x}{-9 \pm 3\sqrt{3}i}\right) \\ = Heun\left(\frac{1 \pm \sqrt{3}i}{2}, \frac{3 \pm \sqrt{3}i}{6}, 1, 1, 1, 1, \frac{-3 \mp \sqrt{3}i}{18} \cdot x\right). \end{aligned} \quad (92)$$

The other operator M_2 has the following (classical modular form, see appendix B) pull-backed ${}_2F_1$ hypergeometric solution analytic at $x = 0$:

$$\begin{aligned} \mathcal{S}_2 = \frac{1}{(1+4x-2x^2-36x^3+81x^4)^{1/4}} \\ \times {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], \frac{1728 \cdot x^5 \cdot (1+9x+27x^2) \cdot (1-2x)^2}{(1+4x-2x^2-36x^3+81x^4)^3}\right) \\ = 1 - x + 3x^2 - x^3 - 29x^4 + 249x^5 - 1329x^6 + 5487x^7 - 16029x^8 \\ + 12149x^9 + 252253x^{10} + \dots \end{aligned} \quad (93)$$

Thus the diagonal of (85) is the *half-sum of the two series* (88) and (93) corresponding to *classical modular forms*:

$$Diag\left(R(x, y, z)\right) = \frac{\mathcal{S}_1 + \mathcal{S}_2}{2}. \quad (94)$$

2.3. Derivatives of classical modular forms

We give here an example of a diagonal of a rational function in three variables yielding a derivative of a classical modular form (or a derivative of a Heun function). Let us consider the following rational function in three variables:

¹⁸Change $x \rightarrow x/27$ to match \mathcal{S}_1 , given by (88), with (92).

$$R(x, y, z) = \frac{3x^3y}{1+x+y+z}. \tag{95}$$

The diagonal of (95) has the following series expansion with *integer coefficients*:

$$-30x^3 + 840x^4 - 20790x^5 + 504504x^6 - 12252240x^7 + 299304720x^8 - 7362064710x^9 + 182298745200x^{10} + \dots \tag{96}$$

The telescoper of this rational function of three variables (95) gives a linear differential operator of order three $L_3 = L_1 \oplus L_2$ that is the direct sum of a linear differential operator of order one L_1 , and a linear differential of operator of order two L_2 , where:

$$\begin{aligned} L_1 &= x \cdot D_x - 1, \\ L_2 &= (1 + 27x) \cdot (1 + 30x) \cdot x \cdot D_x^2 - 3 \cdot x \cdot D_x + 180x + 3. \end{aligned} \tag{97}$$

The operator L_1 admits the solution $y(x) = x$, while the operator L_2 has the following Heun solution:

$$x \cdot Heun\left(\frac{9}{10}, 0, \frac{1}{3}, \frac{2}{3}, 2, 1, -27 \cdot x\right) = x - 30x^3 + 840x^4 - 20790x^5 + 504504x^6 - 12252240x^7 + 299304720x^8 + \dots \tag{98}$$

$$\begin{aligned} &= -x \cdot {}_2F_1\left(\left[\frac{1}{3}, \frac{2}{3}\right], [1], -27 \cdot x\right) \\ &\quad + 2 \cdot x \cdot (1 + 27x) \cdot {}_2F_1\left(\left[\frac{4}{3}, \frac{5}{3}\right], [2], -27 \cdot x\right) \end{aligned} \tag{99}$$

$$= \mathcal{L}_1\left({}_2F_1\left(\left[\frac{1}{3}, \frac{2}{3}\right], [1], -27 \cdot x\right)\right) \tag{100}$$

where:
$$\mathcal{L}_1 = -x - \frac{1 + 27x}{3} \cdot x \cdot \frac{d}{dx}. \tag{101}$$

With this example we see that a Heun function which has a series expansion with *integer coefficients* (or more generally a globally bounded series), may *not* necessarily be a classical modular form¹⁹, and can instead be a *linear differential operator of order one acting on a classical modular form*.

2.4. Generalization of the previous result

Let us recall example 6, and let us consider, instead of the rational function (9), its *homogeneous partial derivative* with respect to one of its four variables:

$$x \cdot \frac{\partial R(x, y, z, w)}{\partial x} = \frac{x \cdot (y + z + w)}{(1 + xy + yz + zw + wx + yw + xz)^2}. \tag{102}$$

The telescoper of this rational function (102) is a linear differential operator of order three M_3 which is homomorphic to the operator of order three L_3 which was the telescoper of the rational function (9). This homomorphism reads:

$$M_3 \cdot \theta = L_1 \cdot L_3 \quad \text{where:} \quad L_1 = (1 - 18x) \cdot \theta + 18x, \tag{103}$$

¹⁹ In the sense defined in appendices A and B.

where θ is the *homogeneous derivative* $\theta = x \cdot D_x$. Consequently the solutions of the order-three linear differential operator M_3 are simply obtained by taking the homogeneous derivative $\theta = x \cdot D_x$ of the solutions of the order-three linear differential operator L_3 . In particular, the diagonal of the rational function (102) is the *homogeneous derivative* of the diagonal of the rational function (9):

$$Diag\left(x \cdot \frac{\partial R(x, y, z, w)}{\partial x}\right) = x \cdot \frac{d}{dx}\left(Diag\left(R(x, y, z, w)\right)\right). \tag{104}$$

The diagonal of (102) will thus be the *homogeneous derivative of the classical modular form* (11). We do not provide a proof, but in the experimental framework the following identity seems to hold for any order- N linear differential operator L :

$$Diag\left(\mathcal{L}\left(R(x, y, z, w)\right)\right) = L\left(Diag\left(R(x, y, z, w)\right)\right), \tag{105}$$

where:
$$L = \sum_{n=0}^N P_n(x) \cdot \theta^n, \quad \mathcal{L} = \sum_{n=0}^N P_n(xyzw) \cdot \Theta^n, \tag{106}$$

with:
$$\theta = x \cdot \frac{d}{dx}, \quad \dots \quad \Theta = w \cdot \frac{\partial}{\partial w}, \tag{107}$$

where the P_n 's are polynomials. This identity can, of course be generalized to the diagonal of rational functions of an arbitrary number of variables. For any Heun function or classical modular form of this paper obtained as a diagonal of a rational function, we can use these identities (104), (105) to get other rational functions that will be *derivatives of Heun functions or classical modular forms*²⁰.

3. Heun function solutions of telescopers of rational functions related to Shimura curves

The rational function in four variables

$$R(x, y, z, w) = \frac{xyz}{1 - xyzw + xyz \cdot (x + y + z) + xy + yz + xz}, \tag{108}$$

has a telescoper that is a linear differential operator of order three:

$$L_3 = 8x \cdot (1 - x) \cdot (1 - 4x) \cdot D_x^3 + 12 \cdot (1 - 10x + 12x^2) \cdot D_x^2 - 6 \cdot (7 - 17 \cdot x) \cdot D_x + 3, \tag{109}$$

which corresponds to the *symmetric square* of a linear differential operator of order two. The solutions of L_3 are thus expressed in terms of the following Heun functions:

$$Heun\left(\frac{1}{4}, \frac{1}{64}, \frac{1}{8}, \frac{3}{8}, \frac{1}{2}, \frac{1}{2}, x\right)^2, \quad x \cdot Heun\left(\frac{1}{4}, \frac{21}{64}, \frac{5}{8}, \frac{7}{8}, \frac{3}{2}, \frac{1}{2}, x\right)^2, \tag{110}$$

or:

$$x^{1/2} \cdot Heun\left(\frac{1}{4}, \frac{1}{64}, \frac{1}{8}, \frac{3}{8}, \frac{1}{2}, \frac{1}{2}, x\right) \cdot Heun\left(\frac{1}{4}, \frac{21}{64}, \frac{5}{8}, \frac{7}{8}, \frac{3}{2}, \frac{1}{2}, x\right). \tag{111}$$

²⁰ Derivatives of modular forms are not modular forms.

The series expansion of the first expression in (110) reads:

$$1 + \frac{1}{4}x + \frac{5}{16}x^2 + \frac{5}{8}x^3 + \frac{2795}{1792}x^4 + \frac{15\,691}{3584}x^5 + \frac{1039\,363}{78\,848}x^6 + \dots \quad (112)$$

While the other Heun functions obtained in this paper are diagonals of rational functions and have globally bounded series expansions, the series expansion (112) is *not*²¹ globally bounded: it cannot be recast into a series with integer coefficients. Hence (112) *cannot be a diagonal* of a rational function since diagonals of rational functions are necessarily globally bounded [1]: it is instead a solution of the telescoper of a rational function. In fact the diagonal of the rational function (108) is *zero*.

The operator (109) is the *symmetric square* of the linear differential operator of order two L_2 :

$$L_2 = D_x^2 + \frac{1 - 10x + 12x^2}{2x \cdot (1 - 4x) \cdot (1 - x)} \cdot D_x - \frac{1 - 3x}{16 \cdot x \cdot (1 - 4x) \cdot (1 - x)}, \quad (113)$$

whose (formal) series expansions at 0, 1, and ∞ do not contain *logarithms*. This linear differential operator of order two L_2 admits the solutions:

$$\begin{aligned} &x^{1/2} \cdot (1 - x)^{-7/8} \cdot {}_2F_1\left(\left[\frac{7}{24}, \frac{11}{24}\right], \left[\frac{5}{4}\right], \frac{27}{4} \cdot \frac{x^2}{(1 - x)^3}\right), \\ &(1 - x)^{-1/8} \cdot {}_2F_1\left(\left[\frac{1}{24}, \frac{5}{24}\right], \left[\frac{3}{4}\right], \frac{27}{4} \cdot \frac{x^2}{(1 - x)^3}\right). \end{aligned} \quad (114)$$

The precise correspondence with the Heun functions in (110) reads:

$$\begin{aligned} &Heun\left(\frac{1}{4}, \frac{1}{64}, \frac{1}{8}, \frac{3}{8}, \frac{1}{2}, \frac{1}{2}, x\right) \\ &= (1 - x)^{-1/8} \cdot {}_2F_1\left(\left[\frac{1}{24}, \frac{5}{24}\right], \left[\frac{3}{4}\right], \frac{27}{4} \cdot \frac{x^2}{(1 - x)^3}\right), \end{aligned} \quad (115)$$

$$\begin{aligned} &Heun\left(\frac{1}{4}, \frac{21}{64}, \frac{5}{8}, \frac{7}{8}, \frac{3}{2}, \frac{1}{2}, x\right) \\ &= (1 - x)^{-7/8} \cdot {}_2F_1\left(\left[\frac{7}{24}, \frac{11}{24}\right], \left[\frac{5}{4}\right], \frac{27}{4} \cdot \frac{x^2}{(1 - x)^3}\right). \end{aligned} \quad (116)$$

The two solutions of the linear differential operator (113) can be used to construct a basis for the space of *automorphic forms*, which can then be used to construct Hecke operators relative to this basis²². The second solution in (114) corresponds to an *automorphic form associated with a Shimura curve* with signature (0, 4, 2, 6) which appears in table 1 in [30]. Hence one obtains *Shimura curves associated to telescopers of rational functions*. More details on Heun functions or ${}_2F_1$ *automorphic forms* associated to *Shimura curves* [31–35] are given in appendix C.

²¹ After a rescaling of the variable.

²² See example 9 in [29] for more details.

4. Conclusion

The examples of diagonals of rational functions in three or four variables, that we presented here, illustrate cases where the diagonal of the rational functions are given by Heun functions having series with *integer coefficients*, and can be expressed either in terms of pullbacked hypergeometric functions that are *classical modular forms*, or *derivatives* of classical modular forms. Furthermore, we constructed in section 2.2, a rational function whose diagonal is given by a Heun function that has already been identified as a ‘period’ of an *extremal rational elliptic surface* [25], and that has also emerged in the context of pullbacked ${}_2F_1$ hypergeometric functions [28]. Finally we have also seen a case where the rational function has a telescoper with Heun function solutions, that can be expressed as pullbacked ${}_2F_1$ hypergeometric functions that are *not* globally bounded, and happen to be associated with one of the 77 cases of *Shimura curves* [30]. Such remarkable ${}_2F_1$ hypergeometric functions solutions of a telescoper of a rational function are *not* diagonals of that rational function since their series are not globally bounded. They can be interpreted as ‘periods’ [36, 37] of an algebraic variety over some non-evanescent²³ cycles.

These examples suggest an *algebraic geometrical* link between the diagonals/solutions of the telescopers, and the original rational functions, and this link should be investigated. This study should help shed light on the geometrical nature of the algebraic varieties associated with the denominators of the rational functions (K3, Calabi-Yau threefolds, extremal rational elliptic surfaces, Shimura varieties). In a forthcoming paper which is a work in progress at the current stage, we intend to introduce an *algebraic geometry approach* that proves to be efficient in explaining this link.

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²³ Diagonals are periods over evanescent cycles.

Appendix A. A nome necessary condition to be a classical modular form: why ${}_2F_1([1/5, 1/5], [1], x)$ is not a classical modular form

Consider the identity:

$$\begin{aligned}
 & {}_2F_1\left(\left[\frac{1}{3}, \frac{2}{3}\right], [1], x\right) \\
 &= (1 + 8x)^{-1/4} \cdot {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], 64 \cdot \frac{x \cdot (1-x)^3}{(1+8x)^3}\right). \tag{A.1}
 \end{aligned}$$

The nome associated to the linear differential operator of order two having ${}_2F_1([1/3, 2/3], [1], x)$ as a solution is given by:

$$Q(x) = x + \frac{5}{9}x^2 + \frac{31}{81}x^3 + \frac{5729}{19\,683}x^4 + \frac{41\,518}{177\,147}x^5 + \frac{312\,302}{1594\,323}x^6 + \dots \tag{A.2}$$

and the nome associated to the operator of order two having ${}_2F_1([1/12, 5/12], [1], x)$ as a solution expands as follows:

$$q(x) = x + \frac{31}{72}x^2 + \frac{20\,845}{82\,944}x^3 + \frac{27\,274\,051}{161\,243\,136}x^4 + \frac{183\,775\,457\,147}{1486\,016\,741\,376}x^5 + \dots \tag{A.3}$$

The two ${}_2F_1$ hypergeometric series are *globally bounded*, the series of the corresponding nomes (A.2) and (A.3) are also *globally bounded*, as one expects for a classical modular form. The identity (A.1) on the other solutions of the linear differential operators annihilating ${}_2F_1([1/3, 2/3], [1], x)$ and ${}_2F_1([1/12, 5/12], [1], p(x))$, gives the following identity on their respective ratio τ

$$\tau\left(\left[\frac{1}{3}, \frac{2}{3}\right], [1], x\right) = \mu \cdot \tau\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], 64 \cdot \frac{x \cdot (1-x)^3}{(1+8x)^3}\right), \tag{A.4}$$

where μ is a constant, which gives after exponentiation:

$$64 \cdot Q(x) = q\left(64 \cdot \frac{x \cdot (1-x)^3}{(1+8x)^3}\right). \tag{A.5}$$

Now, the RHS of (A.5) is *necessarily globally bounded*, which agrees with the globally bounded character of the nome (A.2).

In contrast, let us consider ${}_2F_1([1/5, 1/5], [1], x)$. The corresponding series is *globally bounded*²⁴, however the corresponding nome which reads

$$\begin{aligned}
 Q_{[1/5, 1/5]}(x) &= x + \frac{8}{25}x^2 + \frac{102}{625}x^3 + \frac{4744}{46\,875}x^4 + \frac{81\,914}{1171\,875}x^5 \\
 &+ \frac{63\,094\,248}{1220\,703\,125}x^6 + \frac{11\,003\,093\,386x^7}{274\,658\,203\,125} + \dots \tag{A.6}
 \end{aligned}$$

is *not* globally bounded. Therefore, it is not possible to find any *algebraic (or rational) pull-back* $p(x)$ such that

$$\mu \cdot Q_{[1/5, 1/5]}(x) = q(p(x)), \tag{A.7}$$

²⁴ Any ${}_2F_1(a, b, [c], x)$ with $c = 1$ is globally bounded since it is of *weight zero*: it is of the form ${}_nF_{n-1}$, and has c given by an integer and not a fractional number.

since the RHS of (A.7) is necessarily globally bounded when $\mu \cdot Q_{[1/5,1/5]}(x)$ cannot be globally bounded regardless of the constant μ . In appendix B we give the exhaustive list of these 28 hypergeometric ${}_2F_1$'s related to classical modular curves that were obtained using the necessary condition on the nome explained here.

Appendix B. Special ${}_2F_1$ hypergeometric functions associated with classical modular forms

The Heun functions of this paper can all be rewritten in terms of pullbacked ${}_2F_1$ hypergeometric functions which turn out to correspond to classical modular curves (with the exception of the ‘Shimura’ Heun functions of section 3. These ${}_2F_1$ hypergeometric functions correspond in fact to classical modular forms because they can be rewritten [38] as $\mathcal{A} \cdot {}_2F_1([1/12, 5/12], [1], p(x))$ where the pullback $p(x)$ is in general more involved than simple rational pullbacks, being often algebraic functions. Using the globally bounded nome condition of appendix A, we looked for all possible ${}_2F_1$ hypergeometric functions related²⁵ to pullbacked ${}_2F_1([1/12, 5/12], [1], x)$ (see (A.7)). We give here a list of 28 hypergeometric functions that have series with integer coefficients, that are related to modular forms.

$$\begin{aligned}
 & {}_2F_1\left(\left[\frac{1}{2}, \frac{1}{2}\right], [1], 16x\right), \quad {}_2F_1\left(\left[\frac{1}{2}, \frac{1}{3}\right], [1], 36x\right), \quad {}_2F_1\left(\left[\frac{1}{3}, \frac{1}{3}\right], [1], 27x\right), \\
 & {}_2F_1\left(\left[\frac{1}{3}, \frac{2}{3}\right], [1], 27x\right), \quad {}_2F_1\left(\left[\frac{1}{6}, \frac{1}{2}\right], [1], 432x\right), \quad {}_2F_1\left(\left[\frac{1}{6}, \frac{1}{3}\right], [1], 108x\right), \\
 & {}_2F_1\left(\left[\frac{1}{6}, \frac{2}{3}\right], [1], 108x\right), \quad {}_2F_1\left(\left[\frac{1}{6}, \frac{1}{6}\right], [1], 432x\right), \quad {}_2F_1\left(\left[\frac{1}{6}, \frac{5}{6}\right], [1], 432x\right), \\
 & {}_2F_1\left(\left[\frac{1}{4}, \frac{1}{4}\right], [1], 64x\right), \quad {}_2F_1\left(\left[\frac{1}{4}, \frac{1}{2}\right], [1], 32x\right), \quad {}_2F_1\left(\left[\frac{1}{4}, \frac{3}{4}\right], [1], 64x\right), \\
 & {}_2F_1\left(\left[\frac{1}{8}, \frac{3}{8}\right], [1], 256x\right), \quad {}_2F_1\left(\left[\frac{1}{8}, \frac{5}{8}\right], [1], 256x\right), \quad {}_2F_1\left(\left[\frac{3}{8}, \frac{7}{8}\right], [1], 256x\right), \\
 & {}_2F_1\left(\left[\frac{2}{3}, \frac{5}{6}\right], [1], 108x\right), \quad {}_2F_1\left(\left[\frac{1}{3}, \frac{5}{6}\right], [1], 108x\right), \quad {}_2F_1\left(\left[\frac{1}{2}, \frac{3}{4}\right], [1], 32x\right), \\
 & {}_2F_1\left(\left[\frac{3}{4}, \frac{3}{4}\right], [1], 64x\right), \quad {}_2F_1\left(\left[\frac{5}{8}, \frac{7}{8}\right], [1], 256x\right), \quad {}_2F_1\left(\left[\frac{2}{3}, \frac{2}{3}\right], [1], 27x\right), \\
 & {}_2F_1\left(\left[\frac{5}{6}, \frac{5}{6}\right], [1], 432x\right), \quad {}_2F_1\left(\left[\frac{1}{2}, \frac{5}{6}\right], [1], 144x\right), \quad {}_2F_1\left(\left[\frac{1}{2}, \frac{2}{3}\right], [1], 36x\right) \\
 & {}_2F_1\left(\left[\frac{1}{12}, \frac{7}{12}\right], [1], 1728x\right), \quad {}_2F_1\left(\left[\frac{1}{12}, \frac{5}{12}\right], [1], 1728x\right), \\
 & {}_2F_1\left(\left[\frac{5}{12}, \frac{11}{12}\right], [1], 1728x\right), \quad {}_2F_1\left(\left[\frac{7}{12}, \frac{11}{12}\right], [1], 1728x\right). \tag{B.1}
 \end{aligned}$$

Using this globally bounded condition of the nome criterion, we wrote a program that went through all the values of a and b in $[-1, 1]$ (with small increments like $1/200$), with $c = 1$, singling out the ${}_2F_1$ hypergeometric functions that have series with integer coefficients (or more generally globally bounded), both for the ${}_2F_1$ hypergeometric functions, and for the nome. Running this program returned to us exactly the ${}_2F_1$ hypergeometric functions in the above list (B.1).

²⁵ See [1, 2], and the hypergeometric functions in the previous sections in this paper.

Appendix C. Heun functions solutions of telescopers of rational functions related to Shimura curves

The rational function in four variables

$$R(x, y, z, u) = \frac{xyz u}{uxy + uxz + uyz - xyz + ux^2yz + uxy^2z + uxyz^2 + ux^2y^2z^2}, \tag{C.1}$$

has a telescoper that is a linear differential operator of order three which actually corresponds to the *symmetric square* of a linear differential operator of order two. The solutions of this operator of order two are expressed in terms of the following Heun functions:

$$x^{3/8} \cdot Heun\left(4, \frac{49}{64}, \frac{3}{8}, \frac{7}{8}, \frac{5}{4}, \frac{1}{2}, x\right), \quad x^{1/8} \cdot Heun\left(4, \frac{9}{64}, \frac{1}{8}, \frac{5}{8}, \frac{3}{4}, \frac{1}{2}, x\right),$$

or equivalently, the pullbacked ${}_2F_1$ solutions:

$$\begin{aligned} &x^{3/8} \cdot (1-x)^{-7/8} \cdot {}_2F_1\left(\left[\frac{7}{24}, \frac{11}{24}\right], \left[\frac{5}{4}\right], \frac{-27}{4} \cdot \frac{x}{(1-x)^3}\right), \\ &x^{1/8} \cdot (1-x)^{-1/8} \cdot {}_2F_1\left(\left[\frac{1}{24}, \frac{5}{24}\right], \left[\frac{3}{4}\right], \frac{-27}{4} \cdot \frac{x}{(1-x)^3}\right) \end{aligned} \tag{C.2}$$

similar to (114) but with a different pullback. One recovers the same ‘Shimura’ ${}_2F_1$ hypergeometric function as the one in (114), but with a *different* pullback.

Like the pullback in (114), this last pullback $\frac{-27}{4} \cdot \frac{x}{(1-x)^3}$ is ‘special’ as can be seen in appendix C.1 with equations (C.5) and (C.6).

C.1. The pullbacks in ${}_2F_1\left(\left[\frac{1}{24}, \frac{7}{24}\right], \left[\frac{5}{6}\right], x\right)$ and ${}_2F_1\left(\left[\frac{5}{24}, \frac{11}{24}\right], \left[\frac{7}{6}\right], x\right)$ are special

Like all the *Belyi coverings* [39], the pullback $\frac{27}{4} \cdot \frac{x^2}{(1-x)^3}$ in (114) is ‘special’. It has already been seen to occur in another framework [40], namely²⁶ the walk in a Weyl chamber of the Lie algebra $\mathfrak{sl}_3(\mathbb{C})$. It actually occurs in the well-known ‘kernel equation’ for that particular walk described in [40]

$$G(x, y) + G(0, 0) = G(x, 0) + G(0, y), \tag{C.3}$$

$$\text{where:} \quad G(x, y) = L(x, y) \cdot H(x, y), \tag{C.4}$$

and where the generating function $H(x, y)$ of the walk and the kernel of the walk $L(x, y)$, read respectively:

$$H(x, y) = \frac{1-xy}{(1-x)^3 \cdot (1-y)^3}, \quad L(x, y) = \frac{27}{4} \cdot (y + xy^2 + x^2 - 3xy).$$

Noticeably, $G(x, y)$ is the sum of the particular rational function pullback $w(x) = \frac{27}{4} \cdot \frac{x^2}{(1-x)^3}$ and of another rational function of y :

$$G(x, y) = \frac{27}{4} \cdot \frac{x^2}{(1-x)^3} + \frac{27}{4} \cdot \frac{y}{(1-y)^3}. \tag{C.5}$$

Note that this additional rational function of y corresponds to the duality $x \leftrightarrow 1/x$:

²⁶ See equation $w(x) = \frac{27}{4} \cdot \frac{x^2}{(1-x)^3}$, page 3165 in [40].

$$G(x, y) = L(x, y) \cdot H(x, y) = w(x) - w\left(\frac{1}{y}\right). \tag{C.6}$$

C.2. Identities on Shimura ${}_2F_1$ hypergeometric functions and modular equations

There exists an algebraic series $y(x)$ such that the two hypergeometric (114) (or (C.2)) verify the two following identities:

$$\begin{aligned} w^{3/8} \cdot \rho \cdot y'(x)^{1/2} \cdot x^{3/8} \cdot (1-x)^{1/4} \cdot {}_2F_1\left(\left[\frac{1}{24}, \frac{5}{24}\right], \left[\frac{3}{4}\right], x\right) \\ = y(x)^{3/8} \cdot (1-y(x))^{1/4} \cdot {}_2F_1\left(\left[\frac{1}{24}, \frac{5}{24}\right], \left[\frac{3}{4}\right], y(x)\right), \end{aligned} \tag{C.7}$$

and (with the same ρ and w)

$$\begin{aligned} w^{5/8} \cdot \rho \cdot y'(x)^{1/2} \cdot x^{5/8} \cdot (1-x)^{1/4} \cdot {}_2F_1\left(\left[\frac{7}{24}, \frac{11}{24}\right], \left[\frac{5}{4}\right], x\right) \\ = y(x)^{5/8} \cdot (1-y(x))^{1/4} \cdot {}_2F_1\left(\left[\frac{7}{24}, \frac{11}{24}\right], \left[\frac{5}{4}\right], y(x)\right), \end{aligned} \tag{C.8}$$

where the two complex constants ρ and w are given by $\rho = (7 - 24i)/25$ and $w = 1/\rho^2$. These two complex numbers w and ρ are on the unit circle $|w| = |\rho| = 1$ but are not N th root of unity. The algebraic series $y(x)$ is given by the symmetric genus zero modular equation of level five $P(x, y) = 0$ which is parametrised by:

$$x = x(v) = -\frac{225v^2 + 18v + 1}{135000 \cdot v^6}, \quad y = y(v) = x\left(\frac{11v + 2}{252v - 11}\right). \tag{C.9}$$

The algebraic series $y(x)$ in (C.7) or (C.8), given by the modular equation of level five $P(x, y) = 0$ reads:

$$y(x) = w \cdot x + \left(\frac{172\,937\,w}{168\,750} + \frac{103}{270}\right) \cdot x^2 + \left(\frac{338\,124\,694\,601\,w}{398\,671\,875\,000} + \frac{270\,081\,319}{637\,875\,000}\right) \cdot x^3 + \dots$$

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