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Patterns of deformations of Peregrine breather of order 3 and 4 solutions to the NLS equation with multi parameters

Pierre Gaillard¹ · Mickaël Gastineau²

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Abstract In this article, one gives a classification of the solutions to the one dimensional nonlinear focusing Schrödinger equation (NLS) by considering the modulus of the solutions in the (x, t) plan in the cases of orders 3 and 4. For this, we use a representation of solutions to NLS equation as a quotient of two determinants by an exponential depending on t . This formulation gives in the case of the order 3 and 4, solutions with, respectively 4 and 6 parameters. With this method, beside Peregrine breathers, we construct all characteristic patterns for the modulus of solutions, like triangular configurations, ring and others.

Keywords NLS equation · Peregrine breathers · Rogue waves

Introduction

The rogue waves phenomenon currently exceed the strict framework of the study of ocean's waves [1–4] and play a significant role in other fields; in nonlinear optics [5, 6], Bose–Einstein condensate [7], superfluid helium [8], atmosphere [9], plasmas [10], capillary phenomena [11] and even finance [12]. In the following, we consider the one-dimensional focusing nonlinear equation of Schrödinger (NLS) to describe the phenomena of rogue waves. The first results concerning the

NLS equation date from the Seventies. Precisely, in 1972 Zakharov and Shabat solved it using the inverse scattering method [13, 14]. The case of periodic and almost periodic algebro-geometric solutions to the focusing NLS equation was first constructed in 1976 by Its and Kotlyarov [15, 16]. The first quasi rational solutions of NLS equation were constructed in 1983 by Peregrine [17]. In 1986 Akhmediev, Eleonskii and Kulagin obtained the two-phase almost periodic solution to the NLS equation and obtained the first higher order analogue of the Peregrine breather [18–20]. Other analogues of the Peregrine breathers of order 3 and 4 were constructed in a series of articles by Akhmediev et al. [21–23] using Darboux transformations. The present paper presents multi-parametric families of quasi rational solutions of NLS of order N in terms of determinants of order $2N$ dependent on $2N - 2$ real parameters. The aim of this paper was to try to distinguish among all the possible configurations obtained by different choices of parameters, one those which have a characteristic in order to try to give a classification of these solutions.

Expression of solutions of NLS equation in terms of a ratio of two determinants

We consider the focusing NLS equation

$$iv_t + v_{xx} + 2|v|^2v = 0. \quad (1)$$

To solve this equation, we need to construct two types of functions $f_{j,k}$ and $g_{j,k}$ depending on many parameters. Because of the length of their expressions, one defines the functions $f_{v,\mu}$ and $g_{v,\mu}$ of argument A_v and B_v only in the appendix. We have already constructed solutions of equation NLS in terms of determinants of order $2N$ which we call solution of order N depending on $2N - 2$ real parameters. It is given in the following result [24–27]:

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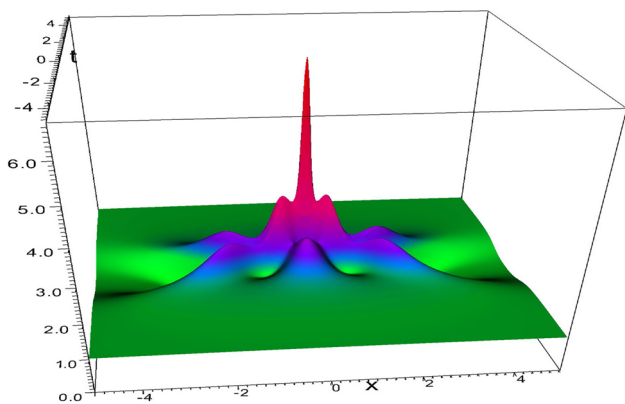


Fig. 1 Solution P_3 to NLS, $N=3$, $\tilde{a}_1 = \tilde{b}_1 = \tilde{a}_2 = \tilde{b}_2 = 0$

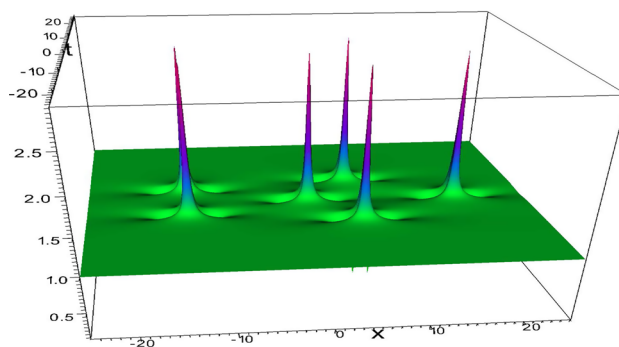


Fig. 4 Solution $1R5 + 1$ to NLS, $N=3$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^6$, $\tilde{b}_2 = 0$

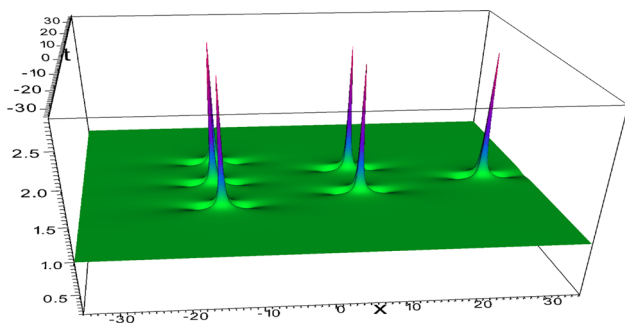


Fig. 2 Solution $1T6$ to NLS, $N=3$, $\tilde{a}_1 = 10^4$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 0$

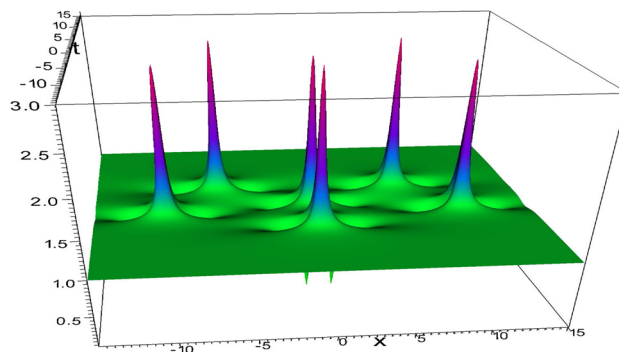


Fig. 5 Solution $1R5 + 1$ to NLS, $N=3$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 10^5$

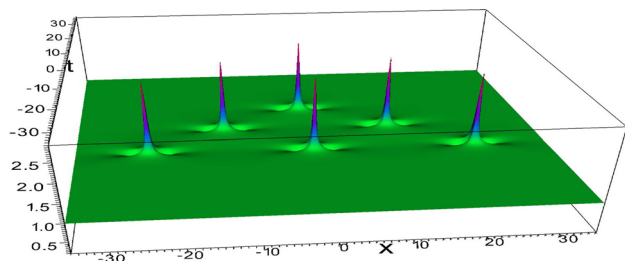


Fig. 3 Solution $1T6$ to NLS, $N=3$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 10^4$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 0$

Theorem 1 The functions v defined by

$$v(x, t) = \frac{\det((n_{jk})_{j,k \in [1,2N]})}{\det((d_{jk})_{j,k \in [1,2N]})} e^{2it - i\varphi} \tag{2}$$

are quasi-rational solution of the NLS Eq. (1) depending on $2N - 2$ parameters $\tilde{a}_j, \tilde{b}_j, 1 \leq j \leq N - 1$, where

$$\begin{aligned} n_{j1} &= f_{j,1}(x, t, 0), \\ n_{jk} &= \frac{\partial^{2k-2} f_{j,1}}{\partial \epsilon^{2k-2}}(x, t, 0), \\ n_{jN+1} &= f_{j,N+1}(x, t, 0), \\ n_{jN+k} &= \frac{\partial^{2k-2} f_{j,N+1}}{\partial \epsilon^{2k-2}}(x, t, 0), \end{aligned}$$

$$\begin{aligned} d_{j1} &= g_{j,1}(x, t, 0), \\ d_{jk} &= \frac{\partial^{2k-2} g_{j,1}}{\partial \epsilon^{2k-2}}(x, t, 0), \\ d_{jN+1} &= g_{j,N+1}(x, t, 0), \\ d_{jN+k} &= \frac{\partial^{2k-2} g_{j,N+1}}{\partial \epsilon^{2k-2}}(x, t, 0), \end{aligned} \tag{3}$$

$2 \leq k \leq N, 1 \leq j \leq 2N$

The functions f and g are defined in (9), (10), (11), (12).

Patterns of quasi rational solutions to the NLS equation

The solutions v_N to NLS Eq. (2) of order N depending on $2N - 2$ parameters \tilde{a}_j, \tilde{b}_j (for $1 \leq j \leq N - 1$) have been already explicitly constructed and can be written as

$$v_N(x, t) = \frac{n(x, t)}{d(x, t)} \exp(2it)$$

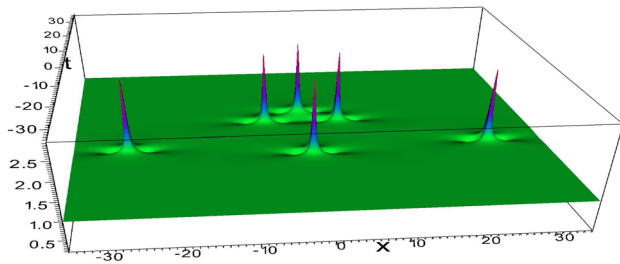


Fig. 6 Solution 1A3 + 1T3 to NLS, $N=3$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 10^4$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 5 \times 10^6$

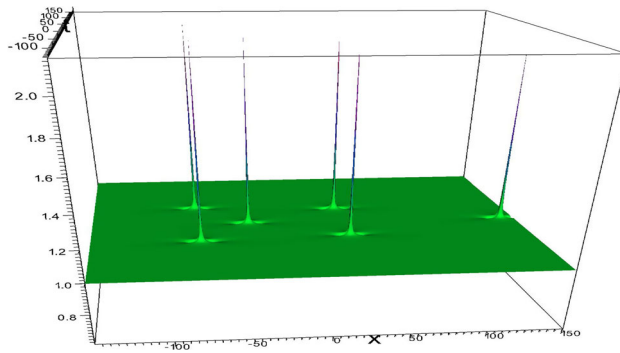


Fig. 7 Solution 1A3 + 1T3 to NLS, $N=3$, $\tilde{a}_1 = 10^6$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^{10}$, $\tilde{b}_2 = 0$

$$= \left(1 - \alpha_N \frac{G_N(2x, 4t) + iH_N(2x, 4t)}{Q_N(2x, 4t)} \right) e^{2it}$$

with

$$G_N(X, T) = \sum_{k=0}^{N(N+1)} g_k(T)X^k,$$

$$H_N(X, T) = \sum_{k=0}^{N(N+1)} h_k(T)X^k,$$

$$Q_N(X, T) = \sum_{k=0}^{N(N+1)} q_k(T)X^k.$$

For order 3 these expressions can be found in [28]; in the case of order 4, they can be found in [29]. In the following, based on these analytic expressions, we give a classification of these solutions by means of patterns of their modulus in the plane $(x; t)$.

Patterns of quasi-rational solutions of order 3 with 4 parameters

P₃ breather

If we choose all parameters equal to 0, $\tilde{a}_1 = \tilde{b}_1 = \dots = \tilde{a}_{N-1} = \tilde{b}_{N-1} = 0$, we obtain the classical Peregrine breather given by

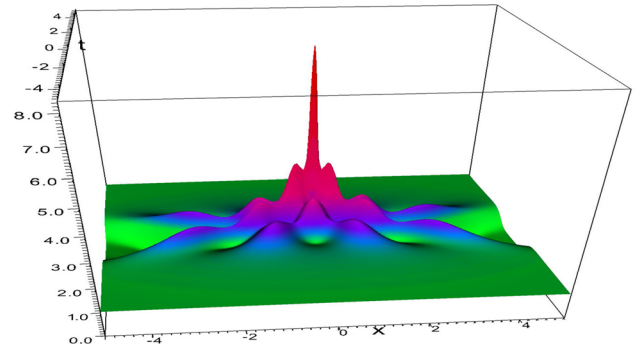


Fig. 8 Solution P_4 to NLS, $N=4$, $\tilde{a}_1 = \tilde{b}_1 = \tilde{a}_2 = \tilde{b}_2 = \tilde{a}_3 = \tilde{b}_3 = 0$

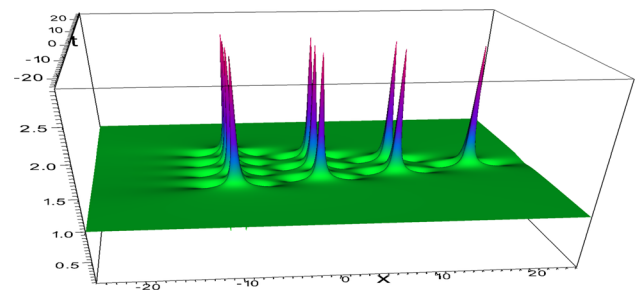


Fig. 9 Solution 1T10 to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 0$, $\tilde{b}_3 = 0$

Triangles

To shorten, the following notations are used: for example, the sequence 1A3 + 1T3 means that the structure has one arc of 3 peaks and one triangle of 3 peaks. If we choose \tilde{a}_1 or \tilde{b}_1 not equal to 0 and all other parameters equal to 0, we obtain triangular configuration with 6 peaks.

Rings

If we choose \tilde{a}_2 or \tilde{b}_2 not equal to 0, all other parameters equal to 0, we obtain ring configuration with peaks.

Arcs

If we choose \tilde{a}_1 and \tilde{a}_2 not equal to 0 and all other parameters equal to 0 (and vice versa, \tilde{b}_1 and \tilde{b}_2 not equal to 0 and all other parameters equal to 0), we obtain deformed triangular configuration which we can call as arc structure.

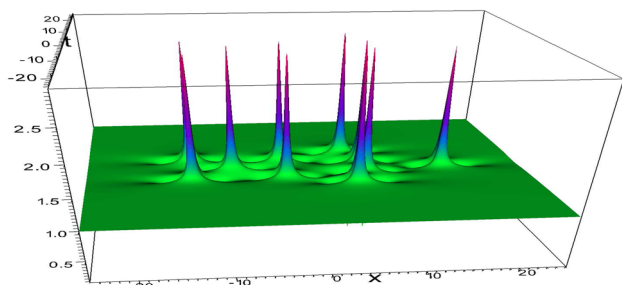


Fig. 10 Solution $2R5/5$ to NLS, $N=4$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^5$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 0$, $\tilde{b}_3 = 0$

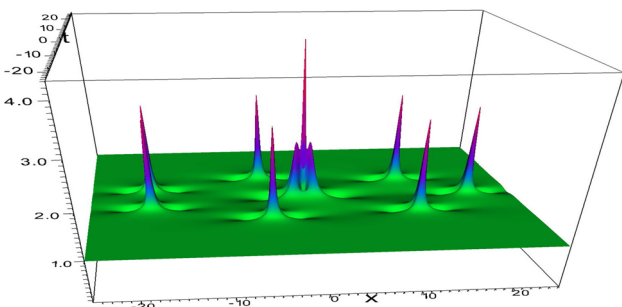


Fig. 11 Solution $1R7+P_2$ to NLS, $N=4$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 10^8$, $\tilde{b}_3 = 0$

Patterns of quasi rational solutions of order 4 with 6 parameters

P_4 breather

If we choose all parameters equal to 0, $\tilde{a}_1 = \tilde{b}_1 = \dots = \tilde{a}_{N-1} = \tilde{b}_{N-1} = 0$, we obtain the classical Peregrine breather given in the following figure.

Triangles

To shorten, we use the notations defined in the previous section. If we choose \tilde{a}_1 or \tilde{b}_1 not equal to 0 and all other parameters equal to 0, we obtain triangular configuration with 10 peaks.

Rings

If we choose \tilde{a}_2 or \tilde{a}_3 not equal to 0 and all other parameters equal to 0 (or vice versa \tilde{b}_2 or \tilde{b}_3 not equal to 0 and all other parameters equal to 0), we obtain ring configuration with 10 peaks.

Arcs

If we choose two parameters non equal to 0, \tilde{a}_1 and \tilde{a}_2 , or \tilde{a}_1 and \tilde{a}_3 not equal to 0, or \tilde{a}_2 and \tilde{a}_3 and all other

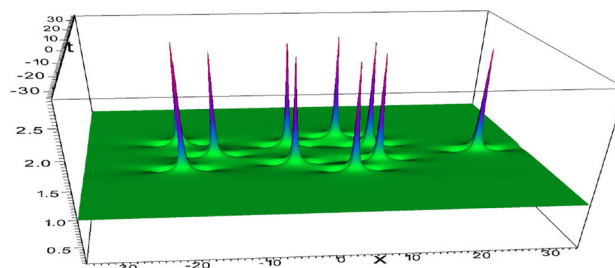


Fig. 12 Solution $2A3/4I+T3$ to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^6$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 0$, $\tilde{b}_3 = 0$

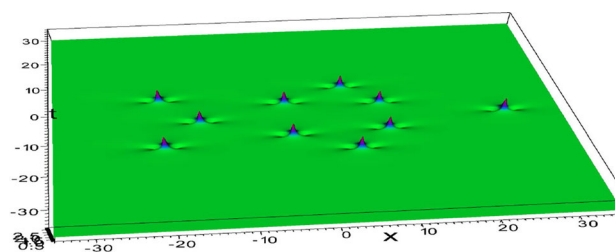


Fig. 13 Solution $2A3/4I+T3$ to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^6$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 0$, $\tilde{b}_3 = 0$, sight top

parameters equal to 0 (or vice versa for parameters b), we obtain arc configuration with 10 peaks.¹

Triangles inside rings

If we choose three parameters non equal to 0, \tilde{a}_1 , \tilde{a}_2 and \tilde{a}_3 and all other parameters equal to 0 (or vice versa for parameters b), we obtain ring with inside triangle.

Conclusion

We have presented here patterns of modulus of solutions to the NLS focusing equation in the (x, t) plane. This study can be useful at the same time for hydrodynamics as well for nonlinear optics; many applications in these fields have been realized, as it can be seen in recent works of Chabchoub et al. [30] or Kibler et al. [31]. This study tries to bring all possible types of patterns of quasi-rational solutions to the NLS equation. We see that we can obtain 2^{N-1} different structures at the order N . Parameters a or b give the same type of structure. For $a_1 \neq 0$ (and other parameters equal to 0), we obtain triangular rogue wave; for $a_j \neq 0$ ($j \neq 1$ and other parameters equal to 0) we get ring rogue wave; in the other choices of parameters, we get in particular arc structures (or claw structure). This type of study has been realized in preceding works. Akhmediev

¹ In the following notations $2A4/3I$, I meaning Reversed.



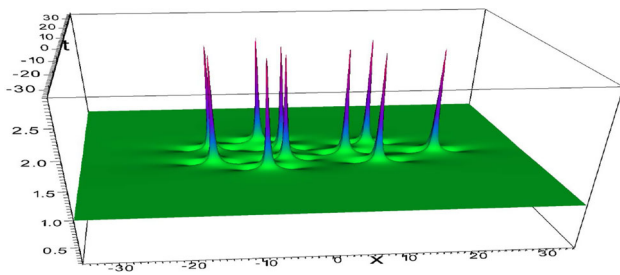


Fig. 14 Solution $2A4/3 + 1T3$ to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 5 \times 10^7$, $\tilde{b}_3 = 0$

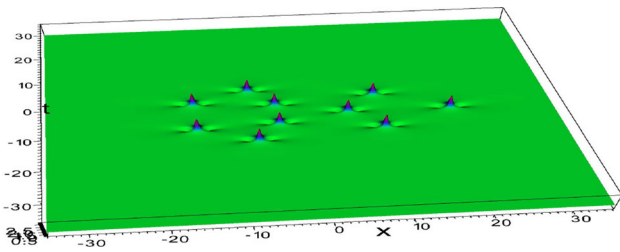


Fig. 15 Solution $2A4/3 + 1T3$ to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 0$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 5 \times 10^7$, $\tilde{b}_3 = 0$, sight top

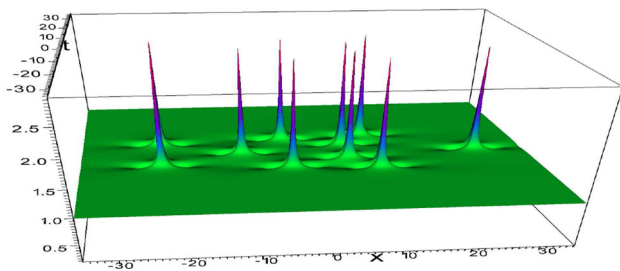


Fig. 16 Solution $2A3/4 + 1T3$ to NLS, $N=4$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^6$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 3 \times 10^8$, $\tilde{b}_3 = 0$

et al, study the order $N = 2$ in [32], $N = 3$ in [33]; the case $N = 4$ was studied in particular ($N = 5, 6$ were also studied) in [34, 35] showing triangle and arc patterns; only one type of ring was presented. The extrapolation was done until the order $N = 9$ in [36]. Ohta and Yang [37] presented the study of the case cas $N = 3$ with rings and triangles. Recently, Ling and Zhao [38] presented the cases $N = 2, 3, 4$ with rings, triangle and also claw structures.

In the present study, one sees appearing richer structures, in particular the appearance of a triangle of 3 peaks inside a ring of 7 peaks in the case of order $N = 4$; to the best of my knowledge, it is the first time that this configuration for order 4 is presented. In this way, we try to bring a better understanding to the hierarchy of NLS rogue wave solutions. It will be relevant to go on this study with higher orders.

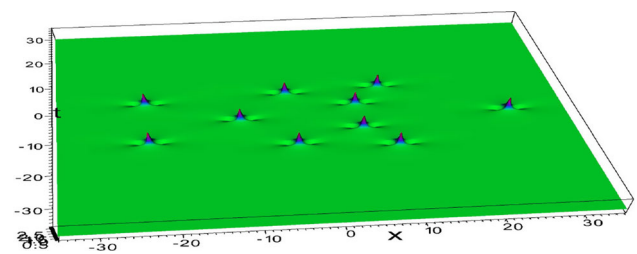


Fig. 17 Solution $2A3/4 + 1T3$ to NLS, $N=4$, $\tilde{a}_1 = 0$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^6$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 3 \times 10^8$, $\tilde{b}_3 = 0$, sight top

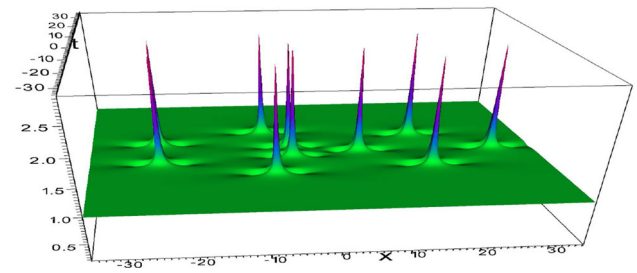


Fig. 18 Solution $1A7 + 1T3$ to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^3$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 10^9$, $\tilde{b}_3 = 0$

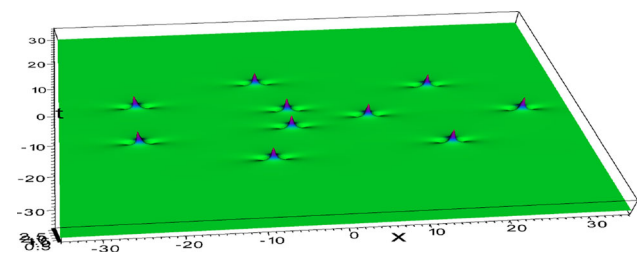


Fig. 19 Solution $1A7 + 1T3$ to NLS, $N=4$, $\tilde{a}_1 = 10^3$, $\tilde{b}_1 = 0$, $\tilde{a}_2 = 10^3$, $\tilde{b}_2 = 0$, $\tilde{a}_3 = 10^9$, $\tilde{b}_3 = 0$, sight top

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Appendix: Parameters and functions

We consider the terms λ_v satisfying the relations for $1 \leq j \leq N$

$$0 < \lambda_j < 1, \lambda_{N+j} = -\lambda_j, \lambda_j = 1 - 2\epsilon^2 j^2,$$

with ϵ a small number intended to tend towards 0. The terms $\kappa_v, \delta_v, \gamma_v$ are functions of the parameters λ_v ,

$1 \leq v \leq 2N$. They are given by the following equations, for $1 \leq j \leq N$:

$$\kappa_j = 2\sqrt{1 - \lambda_j^2}, \quad \delta_j = \kappa_j \lambda_j, \quad (4)$$

$$\gamma_j = \sqrt{\frac{1 - \lambda_j}{1 + \lambda_j}},$$

$$\kappa_{N+j} = \kappa_j, \quad \delta_{N+j} = -\delta_j, \quad (5)$$

$$\gamma_{N+j} = 1/\gamma_j.$$

The terms $x_{r,v}$ $r = 3, 1$ are defined by

$$x_{r,j} = (r-1) \ln \frac{\gamma_j - i}{\gamma_j + i}, \quad (6)$$

$$x_{r,N+j} = (r-1) \ln \frac{\gamma_{N+j} - i}{\gamma_{N+j} + i}.$$

The parameters e_v are given by

$$e_j = ia_j - b_j, \quad e_{N+j} = ia_j + b_j, \quad (7)$$

where a_j and b_j are chosen in the form

$$a_j = \sum_{k=1}^{N-1} \tilde{a}_k \epsilon^{2k+1} j^{2k+1},$$

$$b_j = \sum_{k=1}^{N-1} \tilde{b}_k \epsilon^{2k+1} j^{2k+1}, \quad (8)$$

$$1 \leq j \leq N,$$

with $\tilde{a}_j, \tilde{b}_j, 1 \leq j \leq N-1, 2N-2$, arbitrary real numbers.

The functions $f_{v,1}$ and $g_{v,1}, 1 \leq v \leq N$ are defined by

$$f_{4j+1,1} = \gamma_k^{4j-1} \sin A_1,$$

$$f_{4j+2,1} = \gamma_k^{4j} \cos A_1, \quad (9)$$

$$f_{4j+3,1} = -\gamma_k^{4j+1} \sin A_1,$$

$$f_{4j+4,1} = -\gamma_k^{4j+2} \cos A_1,$$

$$f_{4j+1,N+1} = \gamma_k^{2N-4j-2} \cos A_{N+1},$$

$$f_{4j+2,N+1} = -\gamma_k^{2N-4j-3} \sin A_{N+1}, \quad (10)$$

$$f_{4j+3,N+1} = -\gamma_k^{2N-4j-4} \cos A_{N+1},$$

$$f_{4j+4,N+1} = \gamma_k^{2N-4j-5} \sin A_{N+1},$$

$$g_{4j+1,1} = \gamma_k^{4j-1} \sin B_1,$$

$$g_{4j+2,1} = \gamma_k^{4j} \cos B_1, \quad (11)$$

$$g_{4j+3,1} = -\gamma_k^{4j+1} \sin B_1,$$

$$g_{4j+4,1} = -\gamma_k^{4j+2} \cos B_1,$$

$$g_{4j+1,N+1} = \gamma_k^{2N-4j-2} \cos B_{N+1},$$

$$g_{4j+2,N+1} = -\gamma_k^{2N-4j-3} \sin B_{N+1}, \quad (12)$$

$$g_{4j+3,N+1} = -\gamma_k^{2N-4j-4} \cos B_{N+1},$$

$$g_{4j+4,N+1} = \gamma_k^{2N-4j-5} \sin B_{N+1}.$$

The arguments A_v and B_v of these functions are defined by $1 \leq v \leq 2N$:

$$A_v = \kappa_v x/2 + i\delta_v t - ix_{3,v}/2 - ie_v/2,$$

$$B_v = \kappa_v x/2 + i\delta_v t - ix_{1,v}/2 - ie_v/2.$$

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