Study on Lump Behavior for a New (3+1)-Dimensional Generalised Kadomtsev-Petviashvili Equation

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Abstract. In this paper, we investigate two dimensionally reduced cases of a new (3+1)-dimensional generalised Kadomtsev-Petviashvili equation. With symbolic computation, lump solutions are derived via searching for positive quadratic function solutions to the associated bilinear equations. Localised characteristics and lump motion are analysed and illustrated as well.

AMS subject classifications: 35A25, 35G50, 35Q35, 37K10

Key words: Bilinear method, lump dynamics, dimensionally reduced equation, symbolic computation.

1. Introduction

In the nonlinear science, more and more attention has been paid to the two-dimensional or three-dimensional nonlinear models \[1, 2, 7, 10, 11, 13, 15, 17–21, 23, 24, 26, 28\]. In contrast with the (1+1)-dimensional equations (one for space and the other one for time), multi-dimensional ones are more realistic in describing the nonlinear phenomena in science and engineering \[4–6, 9, 27, 29\]. For example, the Kadomtsev-Petviashvili (KP) equation, modeling water waves of long wavelengths with weakly non-linear restoring forces and
frequency dispersion [10], is usually written as
\[(u_t + 6uu_x + u_{xxx})_x + \sigma u_{yy} = 0, \quad \sigma = \pm 1,\]
which is classified as the KPI equation when \(\sigma = 1\) and the KPII equation when \(\sigma = -1\).

The KP equation is completely integrable, and its soliton solutions and lump solutions have been solved [1, 18].

The KP equation is a two-dimensional generalisation of the Korteweg-de Vries (KdV) equation
\[u_t + 6uu_x + u_{xxx} = 0,\]
where the spatial variable is generalised into two dimensions with \(x\) and \(y\). Actually, more and more generalised KdV or KP equations are proposed, which maybe integrable or non-integrable — cf. Refs. [11, 17, 19–21, 24] and references therein.

The KP-like equation has attracted more attention recently. The generalised perturbation Darboux transformations have been reported for the \((2+1)\)-dimensional KP equation and its extension by using the Taylor expansion of the Darboux matrix [25]. Fission and fusion interaction phenomena of mixed lump kink solutions for a generalised \((3+1)\)-dimensional B-type KP equation has been studied by using the Hirota bilinear method [12].

In recent, a new \((3+1)\)-dimensional generalised KP equation [24] has been introduced as
\[u_{xxxy} + 3(u_xu_y)_x + u_{txx} + u_{tyy} + u_{tzz} - u_{zzz} = 0. \tag{1.1}\]
Via the simplified Hirota bilinear method, multiple soliton solutions to the Eq. (1.1) have been derived with the coefficients of the spatial variables left free, and the phase shifts depending on all these coefficients. It has also been proved that the Eq. (1.1) fails to pass the Painlevé integrability test although it enjoys multiple soliton solutions. Moreover, the resonant multiple wave solutions to the Eq. (1.1) have been constructed by using linear superposition principle [11].

As well known, soliton solutions are exponentially localised in certain directions, while lump solutions are a kind of rational function solutions, localised in all directions in the space [3, 14, 16]. Based on bilinear forms, one can derive both soliton solutions and lump solutions [1, 18]. The dynamics of lump, lumpoff and rogue wave solutions of \((2+1)\)-dimensional Hirota-Satsuma-Ito equations has been studied through bilinear method [30]. For a fourth-order nonlinear generalised Boussinesq water wave equation, symmetry reductions and twelve families of soliton wave solutions have been derived by employing Lie symmetry method [22]. The Riemann-Hilbert approach has also been used to solve \(N\)-soliton solutions of a four-component nonlinear Schrödinger equation associated with a \(5 \times 5\) Lax pair [31].

In this paper, we will focus on the dimensionally reduced cases of Eq. (1.1) and present two classes of lump solutions with symbolic computation. It is clear that the Eq. (1.1) is a \((3+1)\)-dimensional model with the spatial variables \((x, y, z)\) and the time variable \(t\).

Through a dependent variable transformation
\[u = 2[\ln f(x, y, z, t)]_x = 2 \frac{f_x(x, y, z, t)}{f(x, y, z, t)}, \tag{1.2}\]
Eq. (1.1) can be mapped into its Hirota bilinear form as

\[
(D_x^2D_y + D_tD_x + D_tD_y + D_tD_z - D_z^2) f \cdot f = 0, \quad (1.3)
\]

where the derivatives \(D_x^2D_y, D_tD_x, D_tD_y, D_tD_z\) and \(D_z^2\) are bilinear operators \([8]\) defined by

\[
D_x^\alpha D_y^\beta D_z^\delta(f \cdot g) = \left(\frac{\partial}{\partial x} - \frac{\partial}{\partial x'}\right)^\alpha \left(\frac{\partial}{\partial y} - \frac{\partial}{\partial y'}\right)^\beta \left(\frac{\partial}{\partial z} - \frac{\partial}{\partial z'}\right)^\delta \left(\frac{\partial}{\partial t} - \frac{\partial}{\partial t'}\right)^2 \times f(x, y, z, t)g(x', y', z', t') \bigg|_{x'=x, y'=y, z'=z, t'=t}.
\]

In details, we will search for positive quadratic function solutions to the dimensionally reduced forms of the Eq. (1.3) via taking \(z = x\) or \(z = y\), and begin with

\[
f = g^2 + h^2 + a_9, \quad (1.4)
\]

\[
g = a_1 x + a_2 y + a_3 t + a_4,
\]

\[
h = a_5 x + a_6 y + a_7 t + a_8,
\]

where \(a_i (1 \leq i \leq 9)\) are all real parameters to be determined. To obtain the lump solutions, we note that the conditions guaranteeing the well-definedness of \(f\), positiveness of \(f\) and localisation of \(u\) in all directions in the space need to be satisfied. With a selection of the parameters in the solutions, the localised structure and lump motion will be displayed. Finally, a few concluding remarks will be given at the end of the paper.

2. Lump Solutions to the Reduction with \(z = x\)

With \(z = x\), the dimensionally reduced form of the Eq. (1.3) turns out to be

\[
(D_x^2D_y + 2D_tD_x + D_tD_y - D_z^2) f \cdot f = 0, \quad (2.1)
\]

which is transformed into

\[
u_{xxx} + 3(u_xu_y)_x + 2u_{tx} + u_{ty} - u_{xx} = 0, \quad (2.2)
\]

through the link between \(f\) and \(u\)

\[
u = 2[\ln f(x, y, t)]_x = 2\frac{f_x(x, y, t)}{f(x, y, t)}. \quad (2.3)
\]

A direct substitution of \(f\) in the Eq. (1.4) into Eq. (2.1) leads to the following set of constraining equations on the parameters:

\[
\begin{align*}
a_1 &= a_1, \quad a_2 = \frac{a_1^2a_3 - 2a_1a_3^2 + 2a_1a_5a_7 - 2a_1a_7^2 - a_3a_7^2}{a_3^2 + a_7^2}, \quad a_3 = a_3, \quad a_4 = a_4,
\end{align*}
\]
\[ a_5 = a_5, \quad a_6 = -\frac{a_1^2 a_2^2 - 2a_1 a_3 a_5 + 2a_3^2 a_5 - a_3^2 a_7 + 2a_5 a_7^2}{a_3^2 + a_7^2}, \quad a_7 = a_7, \]

\[ a_8 = a_8, \quad a_9 = \frac{3 \left( a_1^2 + a_5^2 \right) \left( a_1 a_3 - 2a_3^2 + a_5 a_7 - 2a_7^2 \right)}{(a_1 a_7 - a_3 a_5)^2}, \quad (2.4) \]

which needs to satisfy the conditions

\[ a_1 a_7 - a_3 a_5 \neq 0, \]
\[ a_1 a_3 - 2a_3^2 + a_5 a_7 - 2a_7^2 > 0 \]

(2.5)

(2.6)

to guarantee the well-definedness of \( f \), the positiveness of \( f \) and the localisation of \( u \) in all directions in the space. The parameters in the set (2.4) yield a class of positive quadratic function solution to the Eq. (2.1) as

\[
\begin{align*}
    f &= \left( a_1 x + \frac{a_1^2 a_3 - 2a_1 a_3 a_5 + 2a_3^2 a_5 - a_3^2 a_7 - 2a_1 a_7^2}{a_3^2 + a_7^2} y + a_3 t + a_4 \right)^2 \\
    &\quad + \left( a_5 x - \frac{a_1^2 a_7 - 2a_1 a_3 a_5 + 2a_3^2 a_5 - a_3^2 a_7 + 2a_5 a_7^2}{a_3^2 + a_7^2} y + a_7 t + a_8 \right)^2 \\
    &\quad + \frac{3 \left( a_1^2 + a_5^2 \right) \left( a_1 a_3 - 2a_3^2 + a_5 a_7 - 2a_7^2 \right)}{(a_1 a_7 - a_3 a_5)^2}, \quad (2.7)
\end{align*}
\]

which, in turn, generates a class of lump solutions to the dimensionally reduced the Eq. (2.2) through transformation (2.3) as

\[
    u^{(i)} = \frac{4(a_1 g + a_5 h)}{f}, \quad (2.8)
\]

where the function \( f \) is defined by the Eq. (2.7), and the functions \( g \) and \( h \) are given as follows:

\[
\begin{align*}
    g &= a_1 x + \frac{a_1^2 a_3 - 2a_1 a_3 a_5 + 2a_3^2 a_5 - a_3^2 a_7 - 2a_1 a_7^2}{a_3^2 + a_7^2} y + a_3 t + a_4, \\
    h &= a_5 x - \frac{a_1^2 a_7 - 2a_1 a_3 a_5 + 2a_3^2 a_5 - a_3^2 a_7 + 2a_5 a_7^2}{a_3^2 + a_7^2} y + a_7 t + a_8.
\end{align*}
\]

3. **Lump Solutions to the Reduction with \( z = y \)**

With \( z = y \), the dimensionally reduced form of the Eq. (1.3) reads

\[
\left( D_x^3 + D_t D_x + 2D_t D_y - D_y^2 \right) f \cdot f = 0, \quad (3.1)
\]

which is cast into

\[
    u_{xxx} + 3(u_x u_y)_x + u_{tx} + 2u_{ty} - u_{yy} = 0 \quad (3.2)
\]

through the link between \( f \) and \( u \), that is, transformation (2.3).
A direct substitution of \( f \) into the Eq. (3.1) gives rise to the following set of constraining equations for the parameters:

\[
\begin{align*}
\{ a_1 &= \frac{a_2^2a_3 - 2a_2a_5^2 + 2a_2a_6a_7 - 2a_2a_7^2 - a_3a_6^2}{a_3^2 + a_7^2}, & a_2 &= a_2, & a_3 &= a_3, & a_4 &= a_4, \\
a_5 &= -\frac{a_2^2a_7 - 2a_2a_3a_6 + 2a_2a_6a_7 - a_3^2a_7 + 2a_6a_7^2}{a_3^2 + a_7^2}, & a_6 &= a_6, & a_7 &= a_7, & a_8 &= a_8, \\
a_9 &= \frac{3(a_2^2 + a_6^2)^2(a_2a_3 - 2a_5^2 + a_6a_7 - 2a_7^2)(a_2^2 - 4a_2a_3 + 4a_3^2 + a_6^2 - 4a_6a_7 + 4a_7^2)}{(a_2a_7 - a_3a_6)^2(a_3^2 + a_7^2)}
\end{align*}
\]

which needs to satisfy the conditions

\[
\begin{align*}
a_2a_7 - a_3a_6 &\neq 0, \\
a_2a_3 - 2a_5^2 + a_6a_7 - 2a_7^2 &> 0
\end{align*}
\]

to guarantee the well-definedness of \( f \), the positiveness of \( f \) and the localisation of \( u \) in all directions in the space. The parameters in the set (3.3) yield a class of positive quadratic function solution to the Eq. (3.1) as

\[
f = \left( \frac{a_2^2a_3 - 2a_2a_5^2 + 2a_2a_6a_7 - 2a_2a_7^2 - a_3a_6^2}{a_3^2 + a_7^2}x + a_2y + a_3t + a_4 \right)^2 + \left( -\frac{a_2^2a_7 - 2a_2a_3a_6 + 2a_2a_6a_7 - a_3^2a_7 + 2a_6a_7^2}{a_3^2 + a_7^2}x + a_6y + a_7t + a_8 \right)^2 + \frac{3(a_2^2 + a_6^2)^2(a_2a_3 - 2a_5^2 + a_6a_7 - 2a_7^2)(a_2^2 - 4a_2a_3 + 4a_3^2 + a_6^2 - 4a_6a_7 + 4a_7^2)}{(a_2a_7 - a_3a_6)^2(a_3^2 + a_7^2)},
\]

which, in turn, generates a class of lump solutions to the dimensionally reduced the Eq. (3.2) through transformation (2.3) as

\[
u^{(1)} = \frac{4(a_1g + a_5h)}{f},
\]

where the function \( f \) is defined by the Eq. (3.5), and the functions \( g \) and \( h \) are given as follows:

\[
\begin{align*}
g &= \frac{a_2^2a_3 - 2a_2a_5^2 + 2a_2a_6a_7 - 2a_2a_7^2 - a_3a_6^2}{a_3^2 + a_7^2}x + a_2y + a_3t + a_4, \\
h &= -\frac{a_2^2a_7 - 2a_2a_3a_6 + 2a_2a_6a_7 - a_3^2a_7 + 2a_6a_7^2}{a_3^2 + a_7^2}x + a_6y + a_7t + a_8.
\end{align*}
\]
4. Localised Characteristics and Lump Motion

The transformations (1.2) and (2.3) [with the Eq. (1.4)] clearly denote that lump solution is a type of rational solution. By virtue of the following property
\[ \lim_{x^2+y^2 \to \infty} f(x, y, t) = \infty \quad \forall t \in \mathbb{R} \]
it is easy to have
\[ \lim_{x^2+y^2 \to \infty} u^{(l)}(x, y, t) = \lim_{x^2+y^2 \to \infty} u^{(li)}(x, y, t) = 0 \quad \forall t \in \mathbb{R}, \]
therefore, all the solutions derived in this paper \((u^{(l)} \text{ and } u^{(li)})\) are rationally localised in all directions in the space.

The amplitude of a lump solution \(u\) is defined as \(\max |u|\), and the location of a lump solution is then defined as the place where the max \(|u|\) is attained. To study the lump motion, we firstly derive all the critical points of the lump solutions at a fixed time \(t\) as
\[
x^*_x(t) = \frac{(a_1^2 + a_5^2)(a_2a_7 - a_5a_6)t + a_2a_8 - a_4a_6}{(a_1^2 + a_5^2)(a_1a_6 - a_2a_5)},
\]
\[
y^*(t) = \frac{(a_3a_5 - a_1a_7)t + a_4a_5 - a_1a_8}{a_1a_6 - a_2a_5},
\]
For the lump \(u^{(l)}\) with parameter constraining conditions (2.4)-(2.6), the second partial derivative test
\[
u_{xx}(x^*_x(t), y^*(t)) = -2 \frac{(a_1^2 + a_5^2)^{3/2}}{a_9^{3/2}} < 0,
\]
\[
u_{xx}(x^*_x(t), y^*(t))u_{yy}(x^*_x(t), y^*(t)) - u_{xy}(x^*_x(t), y^*(t))
\]
\[= 4 \frac{(a_1^2 + a_5^2)^2}{a_9^2} (a_1a_6 - a_2a_5)^2 > 0
\]
tells us that \((x^*_x(t), y^*(t))\) is the maximum point, and
\[
u_{\max} = \frac{2|a_3a_5 - a_1a_7|}{\sqrt{3(a_1^2 + a_5^2)(a_1a_3 - 2a_2^2 + a_5a_7 - 2a_7^2)}}
\]
Meanwhile, we can find
\[
u_{xx}(x^*_x(t), y^*(t)) = 2 \frac{(a_1^2 + a_5^2)^{3/2}}{a_9^{3/2}} > 0,
\]
\[
u_{xx}(x^*_x(t), y^*(t))u_{yy}(x^*_x(t), y^*(t)) - u_{xy}(x^*_x(t), y^*(t))
\]
\[= 4 \frac{(a_1^2 + a_5^2)^2}{a_9^2} (a_1a_6 - a_2a_5)^2 > 0,
\]
so that \((x^*(t), y^*(t))\) is the minimum point, and

\[
    u_{\text{min}} = \frac{-2|a_3 a_5 - a_1 a_7|}{\sqrt{3}(a_1^2 + a_5^2)(a_1 a_3 - 2a_3^2 + a_5 a_7 - 2a_7^2)}.
\]

Hereby, the amplitude of the lump

\[
    u^{(I)} = \frac{2|a_3 a_5 - a_1 a_7|}{\sqrt{3}(a_1^2 + a_5^2)(a_1 a_3 - 2a_3^2 + a_5 a_7 - 2a_7^2)}.
\]

which locates at \((x_1^*(t), y^*(t))\).

Correspondingly, for the lump \(u^{(II)}\) with parameter constraining conditions (3.3)-(3.4), we have the maximum point \((x_2^*(t), y^*(t))\) with

\[
    u_{\text{max}} = \frac{2|a_3 a_6 - a_2 a_7|}{\sqrt{3}(a_2^2 + a_6^2)(a_2 a_3 - 2a_3^2 + a_6 a_7 - 2a_7^2)},
\]

the minimum point \((x_2^*(t), y^*(t))\) with

\[
    u_{\text{min}} = \frac{-2|a_3 a_6 - a_2 a_7|}{\sqrt{3}(a_2^2 + a_6^2)(a_2 a_3 - 2a_3^2 + a_6 a_7 - 2a_7^2)},
\]

and the amplitude of the lump

\[
    u^{(II)} = \frac{2|a_3 a_6 - a_2 a_7|}{\sqrt{3}(a_2^2 + a_6^2)(a_2 a_3 - 2a_3^2 + a_6 a_7 - 2a_7^2)},
\]

which locates at \((x_2^*(t), y^*(t))\).

With particular choices of the involved parameters in the lump solution \(u\), the localised characteristics and lump motion can be seen clearly in Figs. 1 and 2 including (a) three-dimensional structure, (b) density plot and (c) the contour plot with routing display.

![Figure 1: Lump dynamic characteristics of \(u^{(I)}\) via the Eq. (2.8) with \(a_1 = -2, a_3 = -1, a_4 = 0, a_5 = 4, a_7 = 1.5\) and \(a_8 = 0\): (a) 3-dimensional plot with \(t = 0\), (b) density plot of (a), (c) the contour plot with routing display.](attachment:image)
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5. Concluding Remarks

For two reduced cases of the new $(3 + 1)$-dimensional generalised KP equation — cf. the Eq. (1.1), we have directly constructed two classes of lump solutions — cf. Eqs. (2.8) and (3.6) via searching for positive quadratic function solutions to the associated bilinear equations (2.1) and (3.1).

It is interesting to consider the following two questions. Firstly, for the reduction with $z = t$, the Eq. (1.1) is reduced into

$$u_{xxxxy} + 3(u_x u_y)_x + u_{tx} + u_{ty} = 0. \quad (5.1)$$

How to derive lump solutions or how to prove the nonexistence of lump solutions to the Eq. (5.1) is a further question. Secondly, how to derive lump solutions to the $(3 + 1)$-dimensional nonlinear evolution equations, e.g., the Eq. (1.1). Within the framework of this paper, one may suppose

$$f = g^2 + h^2 + k^2 + a_{16}$$

with

$$g = a_1 x + a_2 y + a_3 z + a_4 t + a_5,$$
$$h = a_6 x + a_7 y + a_8 z + a_9 t + a_{10},$$
$$k = a_{11} x + a_{12} y + a_{13} z + a_{14} t + a_{15},$$

which should be substituted directly into the Eq. (1.3) for the purpose of positive quadratic function solutions so as to lump solutions to the Eq. (1.1).

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