

Research paper

Rogue wave and a pair of resonance stripe solitons to a reduced (3+1)-dimensional Jimbo–Miwa equation[☆]Xiaoen Zhang^{a,b}, Yong Chen^{a,b,*}^aShanghai Key Laboratory of Trustworthy Computing, East China Normal University, Shanghai 200062, China^bMOE International Joint Lab of Trustworthy Software, East China Normal University, Shanghai 200062, China

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ABSTRACT

In this paper, a combination of stripe soliton and lump soliton is discussed to a reduced (3+1)-dimensional Jimbo–Miwa equation, in which such solution gives rise to two different excitation phenomena: fusion and fission. Particularly, a new combination of positive quadratic functions and hyperbolic functions is considered, and then a novel nonlinear phenomenon is explored. Via this method, a pair of resonance kink stripe solitons and rogue wave is studied. Rogue wave is triggered by the interaction between lump soliton and a pair of resonance kink stripe solitons. It is exciting that rogue wave must be attached to the stripe solitons from its appearing to disappearing. The whole progress is completely symmetric, the rogue wave starts itself from one stripe soliton and lose itself in another stripe soliton. The dynamic properties of the interaction between one stripe soliton and lump soliton, rogue wave are discussed by choosing appropriate parameters.

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1. Introduction

Rogue waves are large and spontaneous ocean surface waves that occur in the sea and appear out of nowhere and disappear without a trace [1]. In addition to in the open ocean, an optical rogue waves [2–5], and finance rogue waves [6,7] were discussed in recent years. Mathematically, the first and simplest rogue-wave solution was reported in the nonlinear Schrödinger equation by Peregrine [8]. Whereafter, rogue waves to various of Schrödinger equations are presented [9–11], which provided some useful mechanism to the generating of rogue waves and described some dynamics property between second-order breather solution, second order Kuznetsov–Ma breathers (KMBs), Akhmediev breathers (ABs), and Peregrine solitons. Generally speaking, rogue waves are a kind of rational solutions which are localized in both space and time, its lethality is very strong and can lead to devastating impact to the navigation. In order to describe the physical system in a relevant way, there are a new upsurge to research the rogue wave beyond the NLS equation such as the Hirota equation [12], the Sasa–Satsuma equation [13], multi-component Yajima–Oikawa systems [14], AB system [15]. More importantly, most of the rogue waves in higher dimensional models are line rogue waves [16–19], which arise from the constant background and then retreat back to the constant background again. Compared with the rogue wave, lump solution is also a kind of rational solution and have been a research hotspot. Recently, Ma proposed a positive quadratic function to get the lump

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* Corresponding author.

E-mail address: ychen@sei.ecnu.edu.cn (Y. Chen).

solutions, by using this method, some lump solution have been given, such as the KPI equation [20], BKP equation [21], the p-gKP and p-gBKP equations [22], (2+1)-dimensional KdV equation [23]. It is reported that lump solutions will keep their shapes, amplitudes, velocities after the collision with soliton solutions, which means the collision is completely elastic [24]. But recently, Tang showed the lump solution is drowned by a stripe solution [25], which is a completely inelastic. On the basis of different conditions, the collision will vary essentially.

Inspired by the above physical concerns, we focus on a reduced (3+1)-dimensional Jimbo–Miwa equation

$$u_{3x,y} + 3u_y u_{xx} + 3u_x u_{xy} + 2u_{yt} - 3u_{xz} = 0, \tag{1}$$

which is a second member in the entire Kadomtsev–Petviashvili(KP) hierarchy [26]. Different from the KP equation, this equation does not have the Painlevé property as defined by Weiss [27]. It is shown that the symmetry algebra of Eq. (1) is infinite dimensional but has no Kac–Moody–Virasoro loop structure. Although Eq. (1) is non-integrable, many types of solutions have been given [28,29].

The plan of this paper is as follows: Section 2, we present explicit lump solution to the reduced (3+1)-dimensional Jimbo–Miwa equation with the positive quadratic function method. In Section 3, the dynamics property of lump soliton and one stripe soliton is discussed. The rogue wave solution derived from the interaction between the lump solution and a pair of resonance stripe soliton solution is studied in Section 4.

2. Lump solution of reduced (3+1)-dimensional Jimbo–Miwa equation

Under the link between the function f and u :

$$u = 2(\ln f)_x + u_0 \tag{2}$$

Eq. (1) is transformed into the bilinear formulism

$$((D_x^3 + 2D_t)D_y - 3D_x D_z) f \cdot f = 0. \tag{3}$$

Eq. (3) only has one kind of lump solution when spatial variable $z = x$, then Eq. (1) changes into

$$u_{3x,y} + 3u_y u_{xx} + 3u_x u_{xy} + 2u_{yt} - 3u_{xx} = 0, \tag{4}$$

and its corresponding bilinear formulism equals to

$$4f_{yt}f - 4f_y f_t + 2f_{3x,y}f - 2f_{3x}f_y - 6f_{xy}f_x + 6f_{xx}f_{xy} - 6f_{xx}f + 6f_x^2 = 0. \tag{5}$$

To search for quadratic function solution to Eq. (5), we start with

$$f = g^2 + h^2 + a_9, \quad g = a_1x + a_2y + a_3t + a_4, \quad h = a_5x + a_6y + a_7t + a_8, \tag{6}$$

where $a_i, 1 \leq i \leq 9$ are parameters to be determined. A direct symbol calculation with f gives rise to the following relations:

$$\begin{cases} a_3 = \frac{3a_1^2a_2 + 6a_1a_5a_6 - 3a_2a_5^2}{2a_2^2 + 2a_6^2}, & a_7 = \frac{3a_5^2a_6 + 6a_1a_5a_2 - 3a_1^2a_6}{2a_2^2 + 2a_6^2}, \\ a_9 = \frac{(a_2^2 + a_6^2)(a_1^2 + a_5^2)(a_1a_2 + a_5a_6)}{(a_1a_6 - a_2a_5)^2}, \end{cases} \tag{7}$$

and

$$a_2 \neq 0, \quad a_6 \neq 0, \quad a_1a_6 - a_2a_5 \neq 0, \quad a_1a_2 + a_5a_6 > 0 \tag{8}$$

in order to insure the analytical, positive, and rationally localized in all directions in the (x, y) -plane of f .

Substituting Eq. (7) into Eq. (6), we can obtain the expression of the function f :

$$\begin{aligned} f = & (a_1x + a_2y + \frac{3a_1^2a_2 + 6a_1a_5a_6 - 3a_2a_5^2}{2a_2^2 + 2a_6^2}t + a_4)^2 + \frac{(a_2^2 + a_6^2)(a_1^2 + a_5^2)(a_1a_2 + a_5a_6)}{(a_1a_6 - a_2a_5)^2} \\ & + (a_5x + a_6y + \frac{3a_5^2a_6 + 6a_1a_5a_2 - 3a_1^2a_6}{2a_2^2 + 2a_6^2}t + a_8)^2, \end{aligned} \tag{9}$$

then the solution of Eq. (4) can be written as

$$u = \frac{4a_1g + 4a_5h}{g^2 + h^2 + \frac{(a_2^2 + a_6^2)(a_1^2 + a_5^2)(a_1a_2 + a_5a_6)}{(a_1a_6 - a_2a_5)^2}} + u_0, \tag{10}$$

where

$$\begin{aligned} g &= a_1x + a_2y + \frac{3a_1^2a_2 + 6a_1a_5a_6 - 3a_2a_5^2}{2a_2^2 + 2a_6^2}t + a_4, \\ h &= a_5x + a_6y + \frac{3a_5^2a_6 + 6a_1a_5a_2 - 3a_1^2a_6}{2a_2^2 + 2a_6^2}t + a_8. \end{aligned}$$

If and only if conditions (8) are satisfied, Eq. (10) is a lump solution to the equation. The single lump profiles is given in Fig. 1

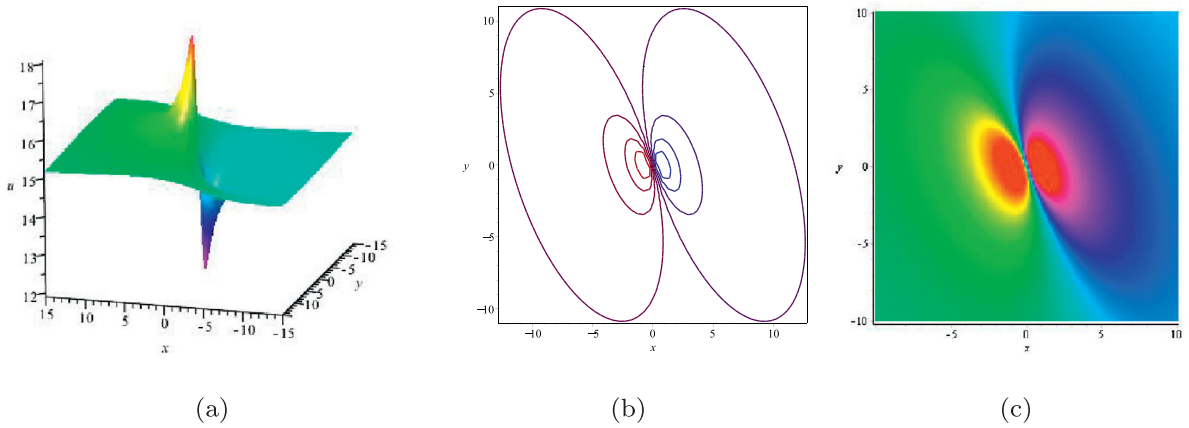


Fig. 1. Evolution plot of the Eq. (10) with the parameters $a_1 = 1.2, a_2 = 0.8, a_4 = 0, a_5 = -0.8, a_6 = 0.4, a_8 = 0, u_0 = 15$. (a) 3d plot, (b) density plot, (c) vertical view.

3. The fusion and fission between lump soliton and one stripe soliton

The lump soliton and one stripe soliton are two kinds of typical local waves in nonlinear system. However the discussing to the interaction of these two local waves are rarely. We want to combine the positive quadratic function and exponential function to discuss their interaction. The results show that there are two different phenomena: fusion and fission, since the difference of the spread direction of stripe soliton.

First, taking

$$f_1 = m_1^2 + n_1^2 + l_1 + a_9, \tag{11}$$

where

$$m_1 = a_1x + a_2y + a_3t + a_4, n_1 = a_5x + a_6y + a_7t + a_8, l_1 = ke^{k_1x+k_2y+k_3t},$$

a direct symbol calculation results in 4 classes of solutions. We only choose one of them to analyze.

$$\begin{cases} a_2 = \frac{a_1k_2^2(a_1^2+a_5^2)}{4a_5^2}, a_3 = \frac{6a_5^2a_1(a_1^2-3a_5^2)}{(a_1^2+a_5^2)^2k_2^2}, a_6 = \frac{k_2^2(a_1^2+a_5^2)}{-4a_5}, a_7 = \frac{6a_5^2(3a_1^2-a_5^2)}{k_2^2(a_1^2+a_5^2)^2}, \\ a_9 = \frac{k_2^2(a_1^2+a_5^2)^2(a_1^4-a_5^4)}{16a_5^2a_1^2}, k_1 = \frac{4a_5^2}{(a_1^2+a_5^2)k_2}, a_8 = 0, a_4 = 0, k_3 = \frac{8a_5^2(3a_1^2-a_5^2)}{(a_1^2+a_5^2)^3k_2^2}, \end{cases}$$

which needs to satisfy the conditions

$$a_5 \neq 0, a_1 \neq 0, k_2 \neq 0, a_1^4 - a_5^4 > 0, \tag{12}$$

to make the corresponding solutions f_1 is positive, analytical and rationally localization in all directions in the (x, y) -plane. Then the solution of Eq. (4) can be given

$$u = \frac{2(2a_1m_1 + 2a_5n_1 + k_1l_1)}{m_1^2 + n_1^2 + l_1 + \frac{k_2^2(a_1^2+a_5^2)^2(a_1^4-a_5^4)}{16a_5^2a_1^2}} + u_0. \tag{13}$$

where

$$\begin{aligned} m_1 &= a_1x + \frac{a_1k_2^2(a_1^2+a_5^2)}{4a_5^2}y + \frac{6a_5^2a_1(a_1^2-3a_5^2)}{(a_1^2+a_5^2)^2k_2^2}t, \\ n_1 &= a_5x + \frac{k_2^2(a_1^2+a_5^2)}{-4a_5}y + \frac{6a_5^2(3a_1^2-a_5^2)}{k_2^2(a_1^2+a_5^2)^2}t, \\ l_1 &= ke^{\frac{4a_5^2}{(a_1^2+a_5^2)k_2}x + k_2y + \frac{8a_5^2(3a_1^2-a_5^2)}{(a_1^2+a_5^2)^3k_2^2}t}. \end{aligned}$$

One can see that Eq. (13) is a combination of polynomial functions and exponential function, it is well known that the order of polynomial function is lower than the exponential function. In order to analyze the dynamics properties of fusion and fission briefly, take the variables x, y as constants and discuss the evolution characteristic.

Obviously, the coefficient of t in l_1 is $\frac{8a_5^2(3a_1^2-a_5^2)}{(a_1^2+a_5^2)^3k_2^2}$, whose sign is only determined by the sign of k_2 with the constraint Eq. (12). The detailed description is presented follows:

(1) In Eq. (13), if $k_2 > 0$, when $t < 0$, the polynomial functions play more important action to the structures of solution than the exponential function and when $t > 0$, the exponential function plays more important role. So it happens fusion as time goes on.

(2) If $k_2 < 0$, it will raise an opposite phenomenon fission whose mechanism is similar to the fusion.

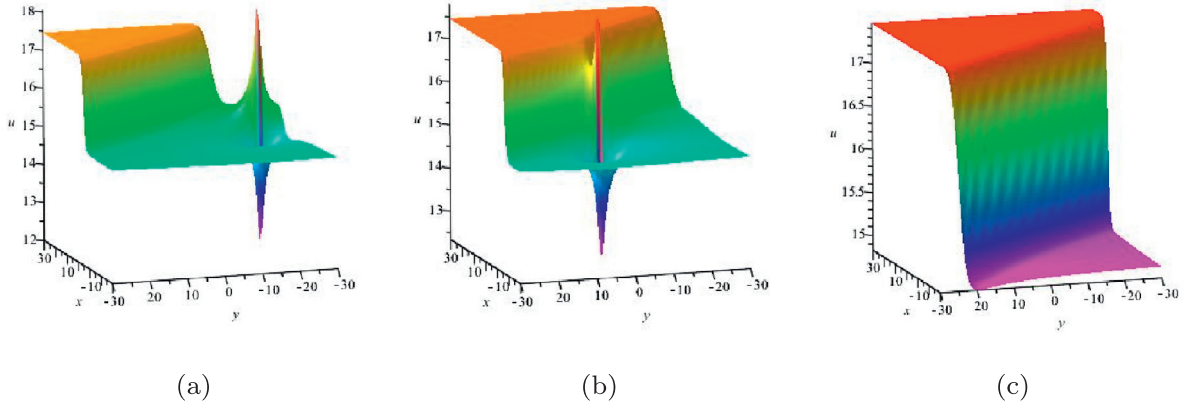


Fig. 2. Evolution plot of the Eq. (13) by choosing $a_1 = 3, a_5 = 2, k = 0.8, k_2 = 1, u_0 = 15$. (a) $t = -10$, (b) $t = 0$, (c) $t = 15$.

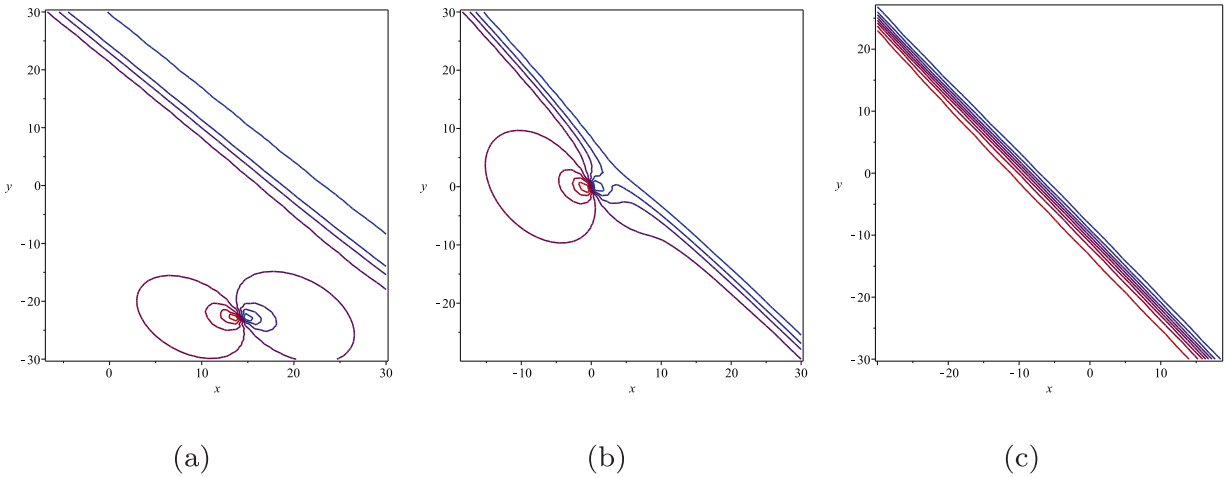


Fig. 3. Density plot of the Eq. (13) by choosing $a_1 = 3, a_5 = 2, k = 0.8, k_2 = 1, u_0 = 15$. (a) $t = -10$, (b) $t = 0$, (c) $t = 15$.

By choosing appropriate values of these parameters, the dynamic graphs of interaction between the lump solution and one-stripe are showed in Figs. 2–5.

Figs. 2 and 4 show the fusion and fission respectively, their corresponding density plots can be seen Figs. 3 and 5. As to fusion, we can find the property that lump soliton with higher energy travels faster and moves across the stripe soliton. After collision, lump soliton and this stripe soliton merge into one stripe soliton. While it is opposite for fission, one stripe soliton splits up into one lump soliton.

4. Rogue wave aroused by the interaction between lump soliton and a pair of resonance kink stripe solitons

In this section, we study the dynamics analysis between lump soliton and a pair of resonance stripe solitons. Assume f as a combination of positive quadratic function and hyperbolic cosine function:

$$f_2 = m_2^2 + n_2^2 + a_9 + l_2, \tag{14}$$

where

$$m_2 = a_1x + a_2y + a_3t + a_4, \quad n_2 = a_5x + a_6y + a_7t + a_8, \quad l_2 = k \cosh(k_1x + k_2y + k_3t),$$

substituting Eq. (14) into Eq. (5), with a direct symbol calculation, we get 13 classes of solution. For brevity, we only list one class of them:

$$a_1 = \frac{a_6 k_1^2}{2}, a_2 = -\frac{2a_5}{k_1^2}, a_3 = \frac{3a_5 k_1^2}{4}, a_7 = -\frac{3a_6 k_1^4}{8}, a_8 = -\frac{a_4 a_6 k_1^2}{2a_5}, a_9 = \frac{2k^2 k_1^2}{k_1^4 a_6^2 + 4a_5^2}, k_2 = \frac{2}{k_1}, k_3 = \frac{k_1^3}{4}$$

which need satisfy

$$k_1 \neq 0, \quad a_5 \neq 0, \quad k > 0. \tag{15}$$

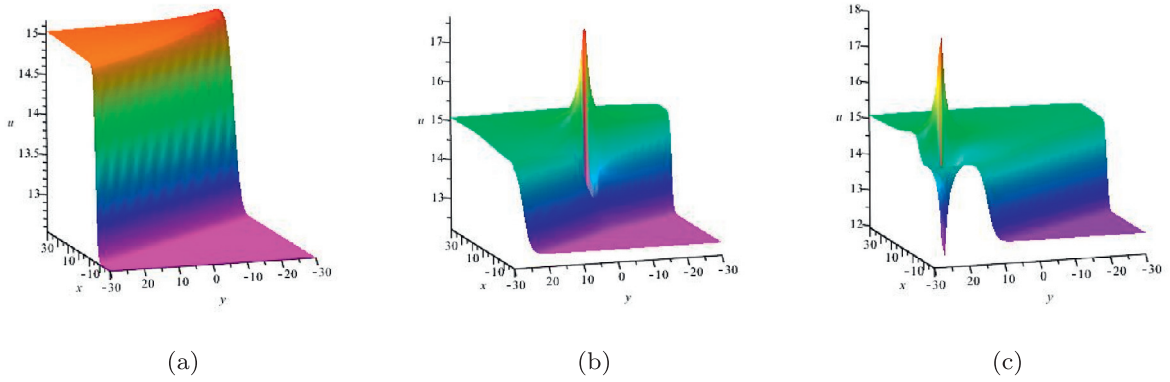


Fig. 4. Evolution plot of the Eq. (13) by choosing $a_1 = 3, a_5 = 2, k = 0.8, k_2 = -1, u_0 = 15$. (a) $t = -15$, (b) $t = 0$, (c) $t = 10$.

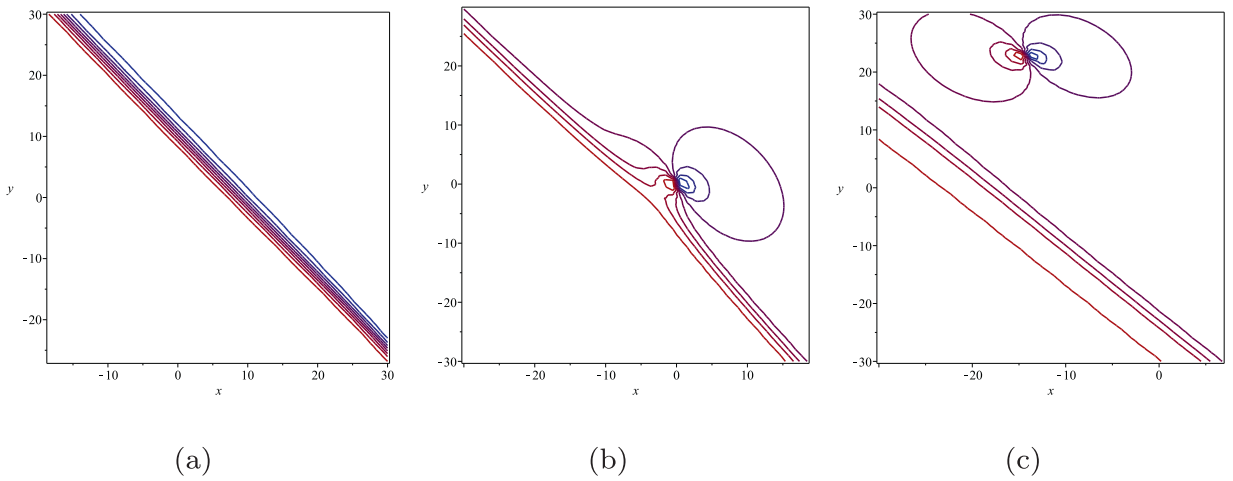


Fig. 5. Density plot of the Eq. (13) by choosing $a_1 = 3, a_5 = 2, k = 0.8, k_2 = -1, u_0 = 15$. (a) $t = -15$, (b) $t = 0$, (c) $t = 10$.

Then we can have the solution to the Eq. (4) with the change $u = 2(\ln f_2)_x + u_0$,

$$u = \frac{2((\frac{a_6 k_1^2}{2}x - \frac{2a_5}{k_1^2}y + \frac{3a_5 k_1^2}{4}t + a_4)k_1^2 a_6 + 2a_5(a_5 x + a_6 y - \frac{3a_6 k_1^4}{8}t - \frac{a_4 a_6 k_1^2}{2a_5}) + k \sinh(k_1 x + \frac{2y}{k_1} + \frac{k_1^3 t}{4})k_1)}{(\frac{a_6 k_1^2}{2}x - \frac{2a_5}{k_1^2}y + \frac{3a_5 k_1^2}{4}t + a_4)^2 + (a_5 x + a_6 y - \frac{3a_6 k_1^4}{8}t - \frac{a_4 a_6 k_1^2}{2a_5})^2 + k \cosh(k_1 x + \frac{2y}{k_1} + \frac{k_1^3 t}{4})k_1} + \frac{2k^2 k_1^2}{k_1^4 a_6^2 + 4a_5^2} + u_0. \tag{16}$$

Next, we analyze the mechanism of the rogue wave, according to Eq. (16), we can know that it is an odd function about variables x, y, t , for simplify, take x, y as constant 0 and the initial phase $a_4 = 0$. So Eq. (16) turns into

$$u_1(t) = \frac{2kk_1 \sinh(\frac{k_1^3 t}{4})}{\frac{9a_6^2 k_1^4 t^2}{16} + \frac{9a_6^2 k_1^8 t^2}{64} + k \cosh(\frac{k_1^3 t}{4}) + \frac{2k^2 k_1^2}{a_6^2 k_1^4 + 4a_5^2}} + u_0. \tag{17}$$

Then the derivative of Eq. (17) is

$$u'_1(t) = \frac{16384k_1^4 (\frac{a_6^2 k_1^4}{4} + a_5^2)(r + s + kk_1^2 \cosh(\frac{k_1^3 t}{4}) + \frac{a_6^2 k k_1^4}{2} + 2a_5^2 k)}{(9a_6^4 k_1^{12} t^2 + 72a_5^2 a_6^2 k_1^8 t^2 + 144a_5^4 k_1^4 t^2 + (64a_6^2 k k_1^4 + 256a_5^2 k) \cosh(\frac{k_1^3 t}{4}) + 128k^2 k_1^2)^2} \tag{18}$$

where

$$r = \frac{9k_1}{16} (\frac{a_6^2 k_1^4}{4} + a_5^2)(k_1^3 t + 8)te \frac{k_1^3 t}{4}, \tag{19}$$

$$s = \frac{9k_1}{16} (\frac{a_6^2 k_1^4}{4} + a_5^2)(k_1^3 t - 8)te \frac{-k_1^3 t}{4},$$

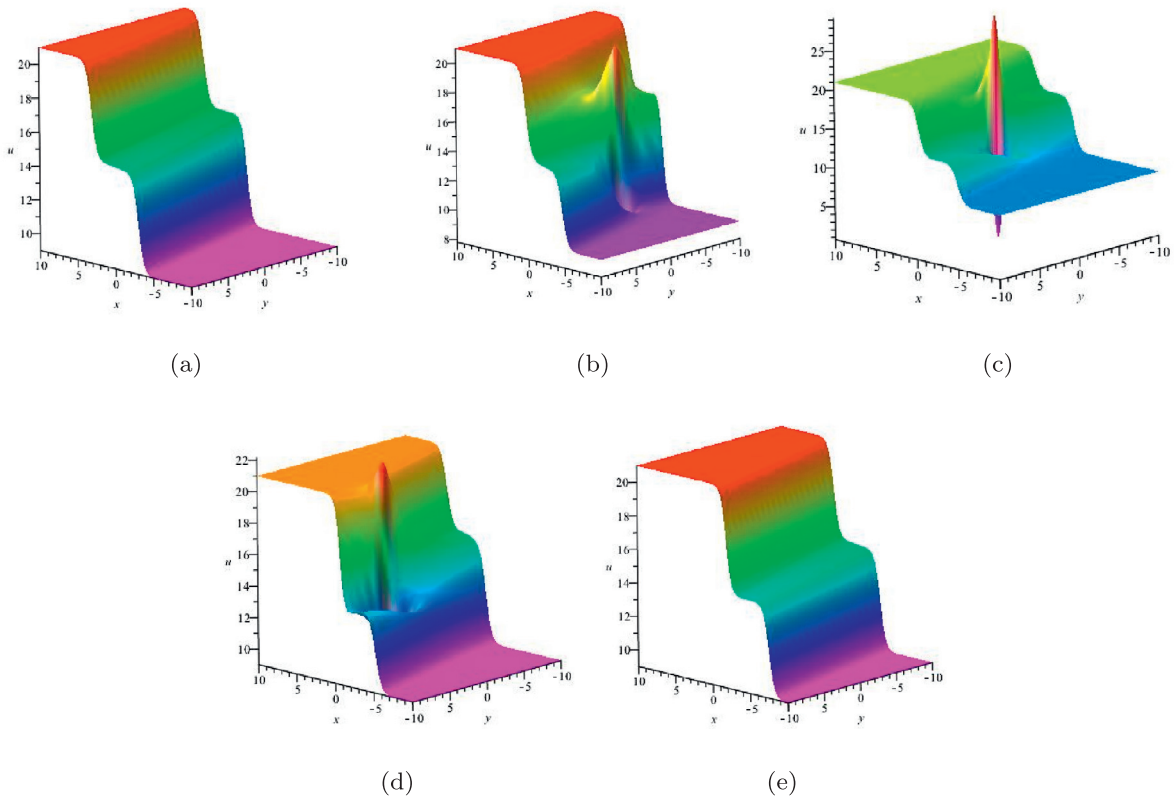


Fig. 6. Evolution plot of the Eq. (16) by choosing $a_4 = 0, a_5 = 5, a_6 = 2, k = 2, k_1 = 3, u_0 = 15$. (a) $t = -1$, (b) $t = -0.12$, (c) $t = 0$, (d) $t = 0.12$, (e) $t = 1$.

apparently, as to Eq. (19), only r and s can be negative with the change of other parameters. No matter $k_1 > 0$ or $k_1 < 0$, when $|t| < |\frac{8}{k_1^3}|$, one of the sign of r and s is negative. Then Eq. (19) will be guaranteed negative when t gets up to an intermediate value of $|t| < |\frac{8}{k_1^3}|$. Furthermore, when $|t| > |\frac{8}{k_1^3}|$ and $t = 0, u'_1(t) > 0$. So $u'_1(t)$ has at least four roots on the basis of that $u'_1(t)$ is an even function, which result in Eq. (17) has at least two maximum value and two minimal value when $|t|$ approximates $|\frac{8}{k_1^3}|$. These extreme points can be generated rogue wave. Its dynamics interaction between lump soliton and a pair of resonance stripe solitons are shown in Figs. 6–8. Fig. 6 demonstrates the mechanism of the rogue wave, (a) and (e) illustrate there are two stripe soliton with invariable propagation, but (a) displays the lump soliton have not appeared, (e) indicates the lump soliton have disappeared. Lump soliton begins to appear and its amplitude increases, which can be seen in (b) and (c), when time is zero, its amplitudes increases the maximum and then decreases. This whole progress is similar to a rogue wave, so we can call this lump soliton as rogue wave. It can be observed that the rogue waves in Fig. 6 have a zero background. That is to say, a localized wave package appears as two resonance solitons with zero background approach zero, and reaches the maximum amplitude (almost several times of the amplitude of the resonance soliton) when time is zero, then decays gradually and disappears finally. Its corresponding density plot and Sectional drawing are presented in Figs. 7 and Fig. 8.

5. Conclusion

In conclusion, we study the exact explicit lump solution, rogue wave solution, the interaction between lump soliton and one stripe soliton and their dynamics characters to a reduced (3+1)-dimensional Jimbo–Miwa equation. The lump solution is obtained by using the bilinear operator and positive quadratic function method, which contains six parameters, four of them should be satisfied some constraints to guarantee the solution positive, analytical, rationally localization from all directions in the (x, y) -plane, others are free, while the rogue wave solution is generated via the interaction between the lump soliton and a pair of resonance stripe solitons. We show that the rogue wave are localized that arise from one stripe soliton and disappear into another stripe soliton.

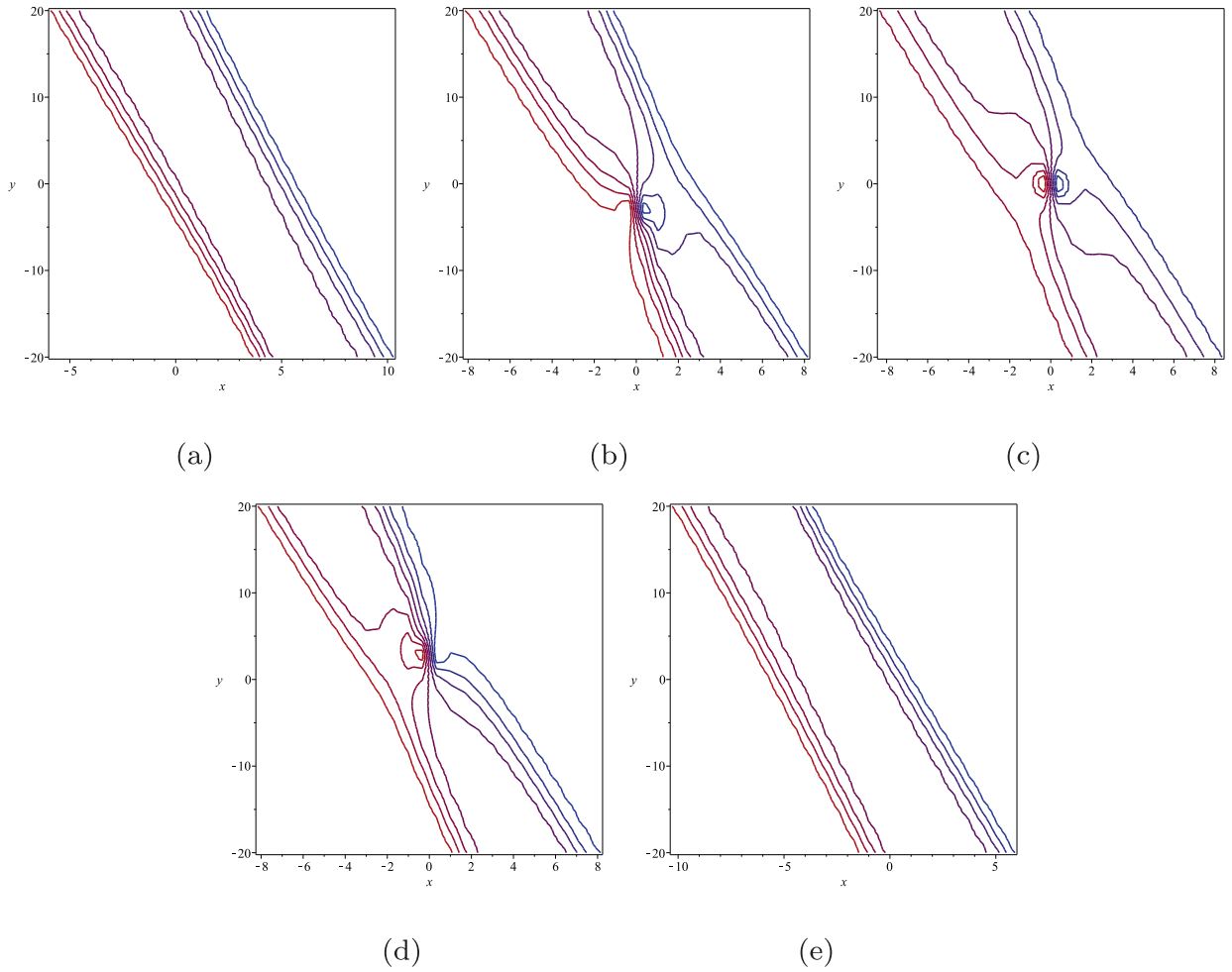


Fig. 7. Density plot of the Eq. (16) by choosing $a_4 = 0, a_5 = 5, a_6 = 2, k = 2, k_1 = 3, u_0 = 15$. (a) $t = -1$, (b) $t = -0.12$, (c) $t = 0$, (d) $t = 0.12$, (e) $t = 1$.

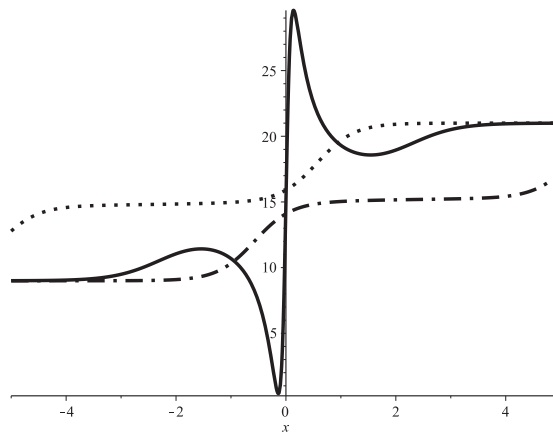


Fig. 8. Sectional drawing of the Eq. (16), broken dotted line indicates $t = -1, y = 0$, dotted line is $t = 1, y = 0$, solid line is $t = 0, y = 0$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Coming to the interaction between lump soliton and one stripe soliton, there are two different physics property, one is fusion, which can be seen in Fig. 2. At first, lump soliton and the stripe soliton are separated from each other. As times goes on, lump soliton begin to be swallowed gradually until disappearing. Another is fission, which is shown in Fig. 4, it is an opposite progress to the fusion. In the beginning, there is only one stripe soliton, when t approximates zero, lump soliton is divided from the stripe soliton until escaping completely. Both of these two progress can loss much more energy than the usual collision.

In the end, we explore the interaction between rogue wave and a pair of resonance kink stripe solitons. Our result shows that two-dimensional rogue wave is excited from two stripe solitons and satisfies the character that "appear from nowhere and disappear without a trace". In addition to, the rogue wave must be trapped in a specific region controlled by the pair of resonance stripe kink solitons, no matter t from ∞ to $-\infty$ or $-\infty$ to ∞ , only and if only t approaches zero, rogue wave can be observed. It should be emphasized that this kind of rogue wave is different from the previous two-dimensional rogue wave, which is only a line rogue wave and is localized referred to a spatial variable, but the obtained rogue is localized on both two spatial variables x and y , which can be seen in Fig. 6. This whole progress provides a mechanism of the rogue wave with the nonlinear equations and is a breakthrough work.

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