Collisional Dynamics of Dromion Triplet for (2+1) Dimensional Coupled Integrable Maccari's System

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Collisional Dynamics of Dromion Triplet for (2+1) Dimensional Coupled Integrable Maccari's System

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Abstract

Using the Truncated Painlevé Approach, this work investigates the (2+1) dimensional coupled integrable Maccari's system. As a result, the solutions are constructed in terms of arbitrary functions. Utilizing the arbitrary functions present in the solution, a variety of localized solutions such as dromion triplet pairs, dromions and rogue waves are generated. The dromion pairs in the two dimensional plane were constructed and their collisional behaviors were explored by selecting the arbitrary functions with adequate initial parameters. In addition to the dromion triplet pairs, dromions and rogue wave solutions were also generated. It is observed that the dromions and rogue waves are unstable and stationary.

Keywords: Dromion triplet pairs, Rogue wave, Truncated Painlevé Approach

1 Introduction

Dromions [1–5] are localized solutions originate at the intersection of two line-solitons [6–13]. In contrast to lumps [14–16] that decay just algebraically, they feature exponentially decaying tails in all directions. Dromions are exponentially localised in both spatial directions, although they can interchange energy during collisions, unlike solitons. These solutions have attracted a lot of attention in the study of nonlinear dynamics since they are driven by boundaries, which means they have time dependent boundary conditions. The Davey–Stewartson I equation [17, 18], which is also termed as two dimensional generalization of the nonlinear Schrödinger equation [19], is a well-known two dimensional nonlinear PDE that admits a dromion solution.

In recent times, researchers are showing more interest to study the nature of Rogue Waves (RWs) [20–24] which are like shock waves [25] and appear only for a short duration of time and they come from nowhere and disappear with no trace. Due to the general devastating impact of oceanic rogue waves, including the fundamental scientific interest in RWs, researchers are attempting to replicate the phenomena in other nonlinear systems. The so-called Peregrine soliton [26], which has a single doubly localized peak on a finite background, is the simplest fundamental solution. The RW investigation has now been widened to include hydrodynamics [27, 28] nonlinear optics [29, 30, 40], plasma physics [32], acoustics [33], Bose-Einstein condensation [34, 35], and even finance [36].

In this paper, one of the influential methods Truncated Painlevé Approach (TPA) [37–40] is utilised to obtain solution of (2+1) dimensional coupled integrable Maccari's System (MS) [41, 42]. MS is a type of Nonlinear Evolution Equation (NLEE) widely used in nonlinear fields to describe the motion of isolated waves localized in a small area of space. Although, it can be constructed from a huge class of NLEEs, MS can be considered as a model system for RW appearance. Attilio Maccari used a reduction method based on Fourier decomposition and space-time rescalings to derive the MS from the Kadomtsev–Petviashvili equation [43]. In other terms, how the MS competes with the nonlinear Schrödinger equation in (2+1) dimensions, as well as the Davey-Stewartson equations in general, when it comes to describing RWs can be seen. Porsezian *et al.* [44] has confirmed the integrability of MS. In recent years, notable advancements have been identified in the study of MS to generate solutions in the closed form. The Exp-function approach [45], the generalised Riccati relation [46], the extended Fan sub-equation method [47], the bilinear method [48], the extended modified auxiliary equation mapping method [49], and closed-form solutions with arbitrary parameters have all been effectively found.

Earlier, TPA has been utilised to solve the (2+1) dimensional LSRI equations [50, 51], NNV equation [52], KdV equation [53], AKNS equation [54], sine-Gordon equation [55], *etc.* The following are the processes involved in using TPA to solve the (2+1) dimensional coupled integrable MS: In terms of the non-characteristic singular manifold, the (2+1) dimensional MS must be transformed into a multilinear equation. The multilinear equation will then be solved and described in closed form as a field variable in form of reduced dimensions arbitrary space and time functions. Localized solutions, such as dromion triplet pairs, dromions, and rogue waves, can be generated by inserting suitable arbitrary functions into the solution.

The preceding is the outline of this paper. In section 2, it is demonstrated how the TPA can be used to solve the (2+1) dimensional coupled integrable MS. Section 3 is devoted to generate various localized excitations using appropriately harnessed arbitrary functions. Finally, section 4 brings the paper to a conclusion.

2 Solution of Coupled Integrable Maccari's System

The (2+1) dimensional coupled integrable Maccari's System is taken in the following form

$$iu_t + u_{xx} + uL = 0, \quad L_t + L_y + |u|_x^2 = 0. \tag{1}$$

By considering, $u = a$ and $u^* = b$, Eq. (1) could be rewritten as

$$ia_t + a_{xx} + aL = 0, \tag{2}$$

$$-ib_t + b_{xx} + bL = 0, \tag{3}$$

$$L_t + L_y + (ab)_x = 0. \tag{4}$$

The following Bäcklund transformation is achieved by truncating the Laurent series of the solutions of Eq. (2) - Eq. (4) at the constant level term.

$$a = \frac{a_0}{\phi} + a_1, \quad b = \frac{b_0}{\phi} + b_1, \quad L = \frac{L_0}{\phi^2} + \frac{L_1}{\phi} + L_2. \tag{5}$$

assuming the following seed solutions

$$a_1 = b_1 = 0, \quad L_2 = L_2(x, \beta), \tag{6}$$

where $\beta = (y - t)$.

Using Eq. (5) and Eq. (6) in Eq. (2) - Eq. (4) and obtaining the coefficients of $(\phi^{-3}, \phi^{-3}, \phi^{-3})$, to find

$$L_0 a_0 + 2a_0\phi_x^2 = 0, \tag{7}$$

$$L_0 b_0 + 2b_0\phi_x^2 = 0, \tag{8}$$

$$a_0 b_0 \phi_x + L_0(\phi_t + \phi_y) = 0. \tag{9}$$

By solving Eq. (7) - Eq. (9), one get

$$L_0 = -2\phi_x^2, \tag{10}$$

$$a_0 b_0 = 2\phi_x(\phi_t + \phi_y). \tag{11}$$

determining the coefficients of $(\phi^{-2}, \phi^{-2}, \phi^{-2})$, one get

$$-ia_0\phi_t + a_0 L_1 - 2a_{0x}\phi_x - a_0\phi_{xx} = 0, \tag{12}$$

$$ib_0\phi_t + b_0 L_1 - 2b_{0x}\phi_x - b_0\phi_{xx} = 0, \tag{13}$$

$$L_{0t} - L_1(\phi_t + \phi_y) + L_{0y} + b_0 a_{0x} + a_0 b_{0x} = 0. \tag{14}$$

By substituting Eq. (10) - Eq.(11) in Eq. (14), the variable L_0 can be obtained as

$$L_1 = -2\frac{\phi_x(\phi_{xt} + \phi_{xy})}{(\phi_t + \phi_y)} + 2\phi_{xx}. \tag{15}$$

With the help of Eq. (15) in Eq. (12) and Eq. (13), variables a_0 and b_0 can be solved as

$$a_0 = F(y,t)\exp\left[\frac{1}{2}\int\left(\frac{(-i\phi_t + \phi_{xx})}{\phi_x} - 2\frac{(\phi_{xt} + \phi_{xy})}{(\phi_t + \phi_y)}\right)dx\right], \tag{16}$$

$$b_0 = F(y,t)\exp\left[\frac{1}{2}\int\left(\frac{(i\phi_t + \phi_{xx})}{\phi_x} - 2\frac{(\phi_{xt} + \phi_{xy})}{(\phi_t + \phi_y)}\right)dx\right], \tag{17}$$

where $F(y,t)$ is a lower dimensional arbitrary function of y and t.

Again, by assembling th coefficients of $(\phi^{-1}, \phi^{-1}, \phi^{-1})$, one may find

$$ia_{0t} + a_{0xx} + L_2 a_0 = 0, \tag{18}$$

$$-ib_{0t} + b_{0xx} + L_2 b_0 = 0, \tag{19}$$

$$L_{1t} + L_{1y} = 0. \tag{20}$$

By substituting Eq. (15) in Eq. (20), the following trilinear form can be obtained

$$\begin{aligned} &\phi_x[(\phi_{xtt} + \phi_{xyy} + 2\phi_{xyt})(\phi_t + \phi_y) - (\phi_{xt} + \phi_{xy})(\phi_{tt} + \phi_{yy} + 2\phi_{yt})] \\ &\quad +(\phi_t + \phi_y)[(\phi_{xt} + \phi_{xy})^2 - (\phi_t + \phi_y)(\phi_{xxt} + \phi_{xxy})] = 0. \end{aligned} \tag{21}$$

The Eq. (21) can be solved as

$$\phi = \phi_1(x, y - t) + \phi_2(y), \tag{22}$$

where $\phi_1(x, y-t)$ and $\phi_2(y)$ are lower dimensional arbitrary functions of space and time.

gathering the coefficients of (ϕ^0, ϕ^0, ϕ^0), to find

$$L_{2t} + L_{2y} = 0. \tag{23}$$

One could examine the correctness of Eq. (18) and Eq. (19) using Eq. (22) in Eq. (16) and Eq. (17), and so L_2 can be resolved using Eq. (23).

$$L_2 = -\left[\frac{1}{2}\int \frac{\phi_{1\beta\beta}\phi_{1x} - \phi_{1\beta}\phi_{1x\beta}}{\phi_{1x}^2}dx\right] + \frac{2\phi_{1xxx}\phi_{1x} - \phi_{1xx}^2 - \phi_{1\beta}^2}{4\phi_{1x}^2}, \tag{24}$$

with a condition

$$F(y,t) = F_1(y). \tag{25}$$

By using Eq. (16), Eq. (17) and Eq. (22) in Eq. (11) to get

$$F_1^2(y) = 2\phi_{2y} \tag{26}$$

and

$$F_1 = \sqrt{2\phi_{2y}}. \tag{27}$$

Eq. (16), Eq. (17), Eq. (22), Eq. (25) and Eq. (27) are used in Eq.(5) to obtain a general functional separation solution of Eq.(2) as

$$a = \frac{\sqrt{2\phi_{2y}}\exp\left[\frac{1}{2}\int \frac{-i\phi_{1\beta}+\phi_{1xx}}{\phi_{1x}}dx\right]}{\phi_1(x,y-t)+\phi_2(y)}, \tag{28}$$

$$b = \frac{\sqrt{2\phi_{2y}}\exp\left[\frac{1}{2}\int \frac{i\phi_{1\beta}+\phi_{1xx}}{\phi_{1x}}dx\right]}{\phi_1(x,y-t)+\phi_2(y)}, \tag{29}$$

$$\begin{aligned} L = & \frac{-2\phi_{1x}^2}{(\phi_1(x,y-t)+\phi_2(y))^2} + \frac{2\phi_{1xx}}{(\phi_1(x,y-t)+\phi_2(y))} \\ & -\left[\frac{1}{2}\int \frac{\phi_{1\beta\beta}\phi_{1x} - \phi_{1\beta}\phi_{1x\beta}}{\phi_{1x}^2}dx\right] + \frac{2\phi_{1xxx}\phi_{1x} - \phi_{1xx}^2 - \phi_{1\beta}^2}{4\phi_{1x}^2}. \end{aligned} \tag{30}$$

From Eq. (28) and Eq. (29), the squared magnitude u can be expressed as

$$|u|^2 = \frac{2\phi_{1x}\phi_{2y}}{(\phi_1(x,y-t)+\phi_2(y))^2}. \tag{31}$$

Because of the arbitrariness of the functions $\phi_1(x,y-t)$ and $\phi_2(y)$, the structure of $|u|^2$ shown by Eq. (31) is quite rich. Some special examples are discussed here.

3 Localized solutions of (2+1) dimensional Coupled Integrable Maccari's System

3.1 Dromion Triplet Pairs

3.1.1 Case (i)

By setting the arbitrary functions $\phi_1(x, y-t)$ and $\phi_2(y)$, the dromion triplet pairs are constructed for the component $|u|^2$ and shown in Fig. 1.

$$\begin{aligned} \phi_1(x,y-t) = sech^2(p_1 x) + p_2 sech^2(p_1 x - p_3(y-t)) + \\ p_5 sech^2(p_1 x + p_3(y-t)), \end{aligned} \tag{32}$$

$$\phi_2(y) = 1 + sech^2(p_4 y). \tag{33}$$

In Fig. 1, it is noted that the three dromion pairs are having unequal amplitudes. At time $t = -100$, the three pairs are well separated. During the time evolution, The bigger pair switches from negative x to positive x axis. At the same time, the smaller one switches in the opposite direction and the middle pair remains stationary. At time $t = 0$, all the three pairings interact in a balanced manner without transferring energy. The animation clip showing collisional dynamics of dromion triplet pairs is available in the link https://youtu.be/4bQEgFojZN4. It is noticed that the pairs are moving only along the x-direction. Recently, Radha *et al.* have constructed the dromion triplet pairs for (2+1) dimensional AKNS [54] and sine-Gordon systems [55]. In the AKNS system, dromion pairs are restricted to move only along the x-direction which undergoes elastic collisions. But, for the sine-Gordon system, it is quite interesting to note that pairs are taking a diagonal path in the x–y plane which undergo inelastic collision. This is supposed to be a distinguishing attribute of them, and it is engraved in their structure.

3.1.2 Case (ii)

For the selection of arbitrary functions $\phi_1(x, y-t)$ and $\phi_2(y)$ in the following form with different arbitrary constants, we have obtained another interesting class of dromion triplet pairs shown in Fig. 2.

$$\begin{aligned} \phi_1(x,y-t) = p_1 sech^2(p_3 x + p_1(y-t)) + p_4 sech^2(p_3 x - p_2(y-t)) + \\ p_5 sech^2(p_3 x + p_2(y-t)), \end{aligned} \tag{34}$$

$$\phi_2(y) = 1 + sech^2(p_3 y). \tag{35}$$

From Fig. 2, it is noted that the dromion triplet pairs are all dynamic and in contrast to case (i) as the middle one was found to be stationary. Furthermore, the amplitude of the middle pair is greater than that of the other two pairs. At the time $t = -40$, the pair with the lower amplitude flows in the positive x direction, while the other two flow in the negative x direction. All the three

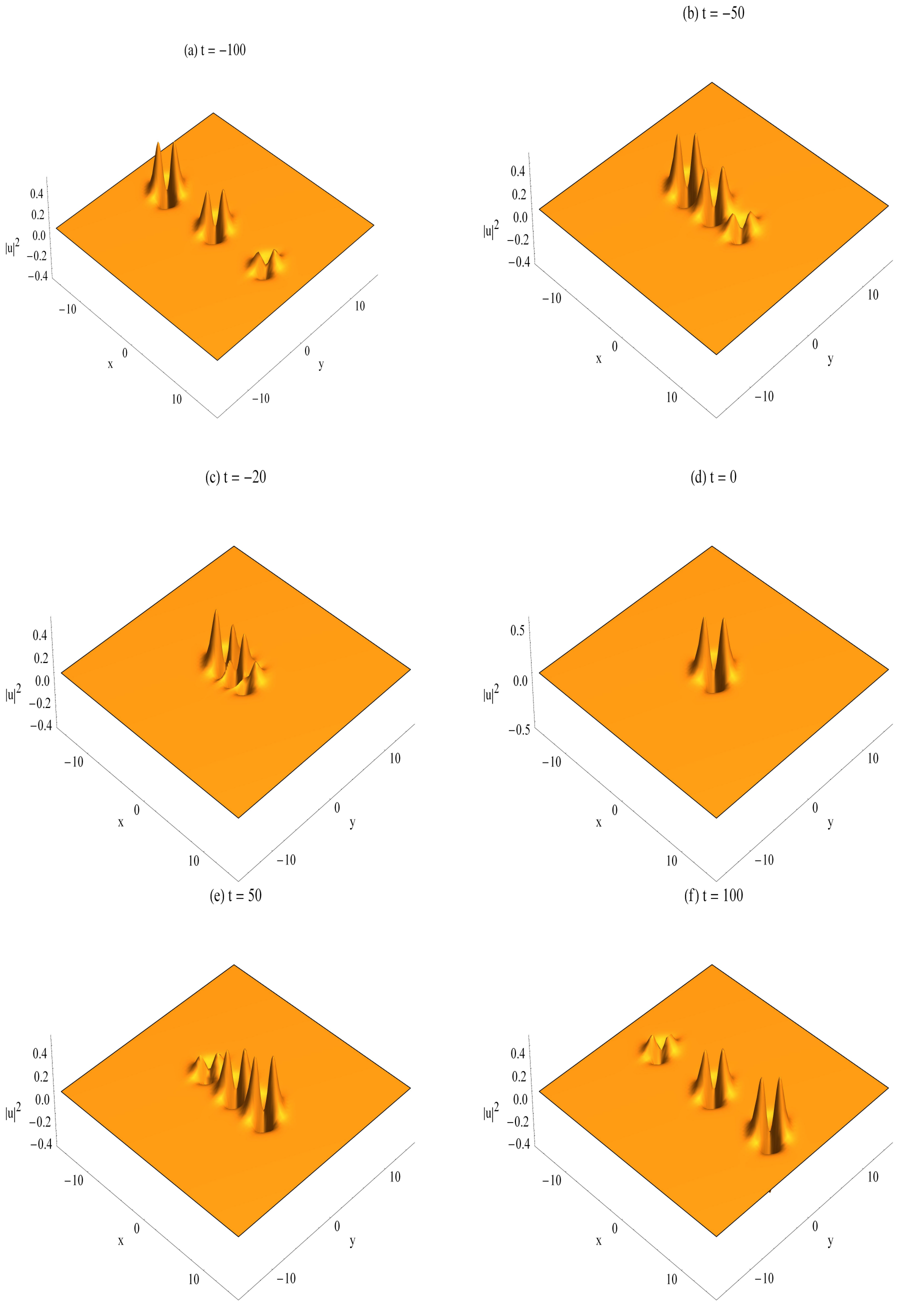

Fig. 1 dromion triplet pairs for the component $|u|^2$ by using Eqs. (32) and (33) with the arbitrary constants $p_1 = 1.3$; $p_2 = 0.25$; $p_3 = 0.12$; $p_4 = 1.1$; $p_5 = 2$ at t = - 100; t = -50; t = -20; t = 0; t = 50; t = 100.

pairs interact elastically without exchanging energy at $t = 0$. Following the collision, the pair with the lesser amplitude proceeds in a negative x direction, whereas the other two pairs proceed in a positive x direction.The site provides an animation clip of dromion triplet pairs corresponding (https://youtu.be/giaPND0ci4E).

3.2 Dromion solution

By selecting the arbitrary functions $\phi_1(x, y-t)$ and $\phi_2(y)$ as given in Eq. (36) and Eq. (37), exponentially localized nonlinear wave structure so called dromion is constructed. With the suitable parameters, the dromion wave pattern is obtained. When the value of t is changed, the width of the dromions is invariant as depicted in Fig. 3. The amplitude of dromion can be adjusted by manipulating the control parameters present in the solution. It is seen that the amplitude of the dromion is found to be small at time $t = -100$, then it becomes high at $t = 0$ and further, the amplitude decreases at $t = -150$. The wave pattern is found to be stationary during the time evolution.

$$\phi_1(x, y-t) = exp(tanh(p_1 x) + p_2(y-t)), \tag{36}$$

$$\phi_2(y) = exp(tanh(p_3 y)) + p_4. \tag{37}$$

3.3 Rogue wave solution

With the selection of the arbitrary functions $\phi_1(x, y-t)$ and $\phi_2(y)$ given in Eq. (38) and Eq. (39),the RWs can be generated. At $t = 0$, RWs having extremely small amplitude as portrays in Fig. 4 can be observed. Also, RW characteristics are almost same for $t = 10$ and $t = -10$. The RW dynamics for component u is demonstrated in Eq. (1). Through controlling the values of arbitrary constants, one can control the dynamics of RWs.

$$\phi_1(x, y-t) = \frac{p_1(y-t)^2}{p_3(\alpha x^2+\beta)^2}, \tag{38}$$

$$\phi_2(y) = \frac{p_2}{(p_4\gamma)^2((p_4 y)^2+\beta)^2}. \tag{39}$$

From Fig. 4, it is noted that the amplitude of RW is very high at time $t = -10$ and $t = 10$. The sudden fall in amplidue is observed at time $t = 0$. Also, the RWs are found to be stationary and they do not move anywhere during the time evolution.

4 Conclusion

In this paper, the TPA is used to explore the solutions of (2+1) dimensional coupled integrable Maccari's System. Then, the localized solutions such as

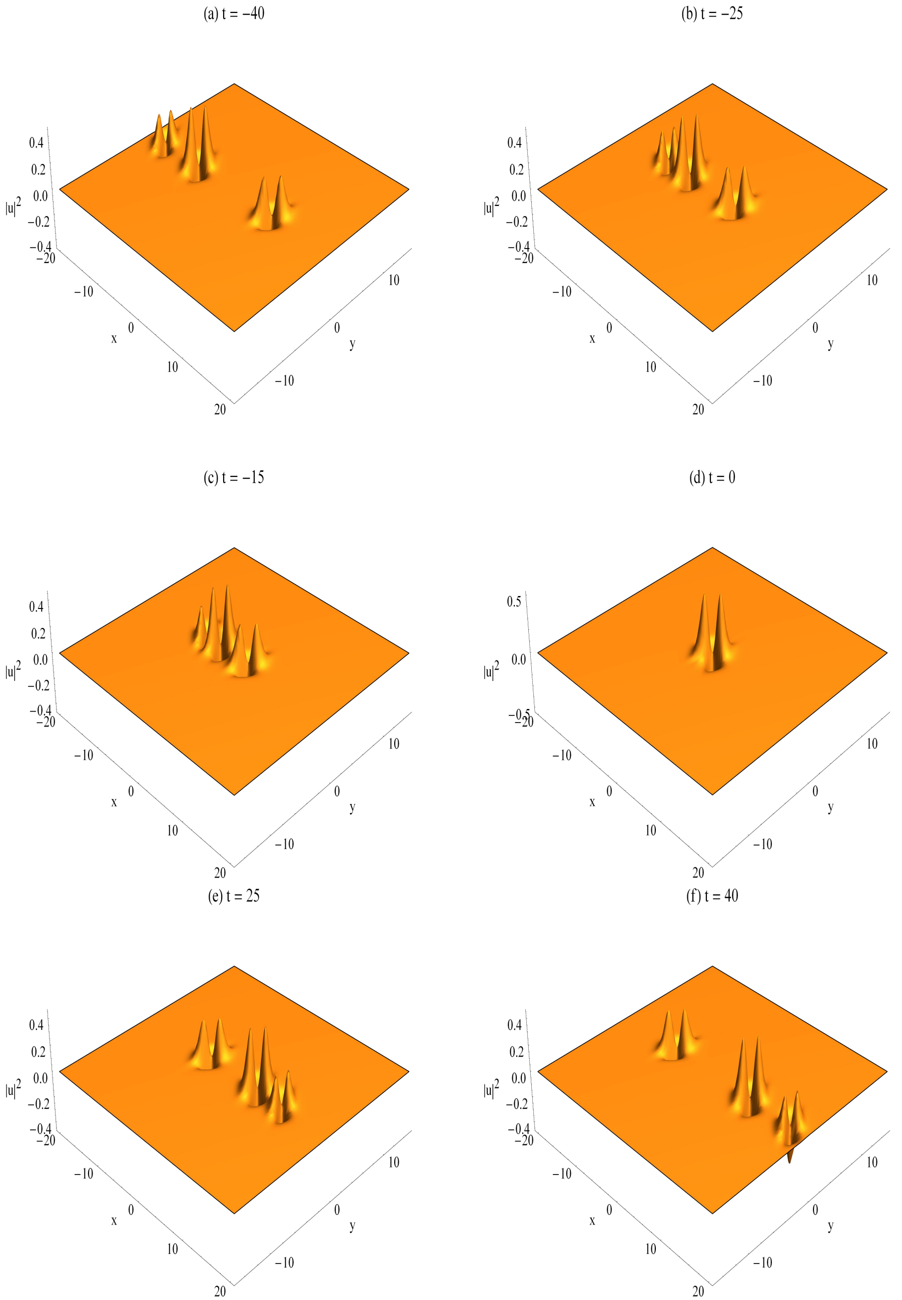

Fig. 2 dromion triplet pairs for the component $|u|^2$ by using Eqs. (34) and (35) with the arbitrary constants p_1 = 0.5; p_2 = 0.25; p_3 = 1.2; p_4 = 0.7; p_5 = 1.7 at t =- 40; t = -25; t = -15; t = 0; t = 25; t = 40.

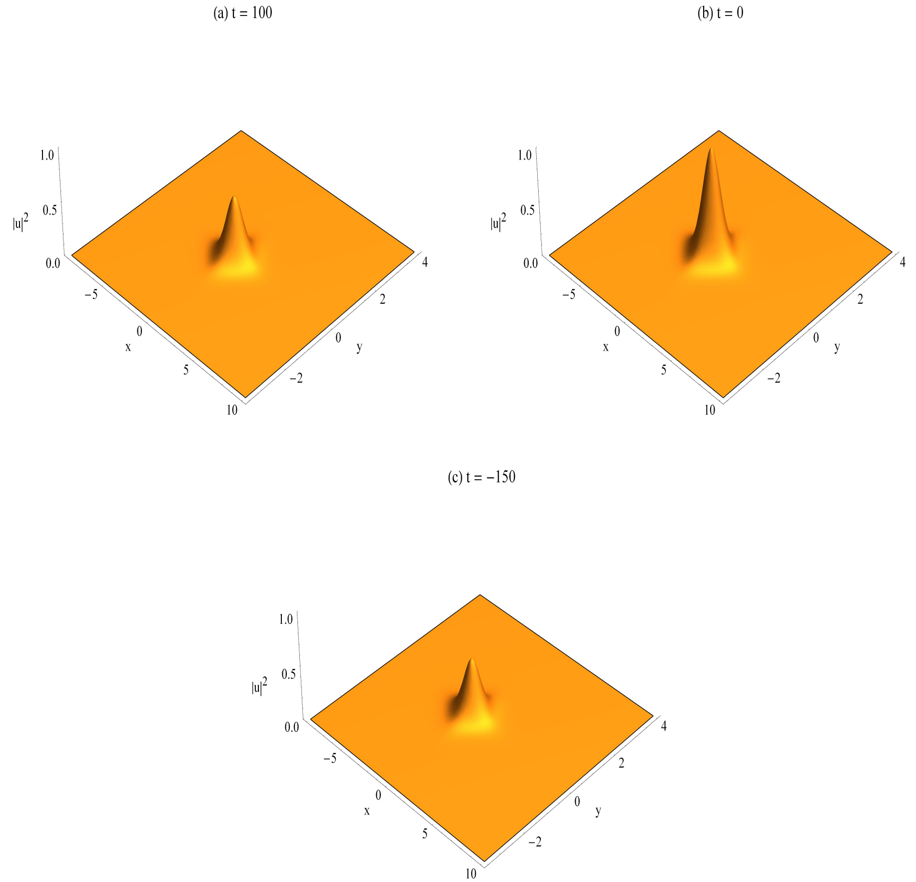

Fig. 3 Dromion for the component $|u|^2$ by using Eqs. (36) and (37) with the arbitrary constants $p_1 = 1$; $p_2 = 0.015$; $p_3 = 2.5$; $p_4 = 0.25$ at t = 100; t = 0; t = -150.

dromion triplet pairs, dromions, and rogue wave patterns are demonstrated. Importantly, the collisional dynamics of dromion triplet pairs are discussed using appropriately harnessed lower-dimensional arbitrary functions of space and time. It is noted that the dromion triplet pairs have undergone inelastic collision during the time evolution. The dromion triplet pairs for (2+1) dimensional coupled integrable Maccari's System have never been brought to the fore in the literature. The dromion pairs in the two-dimensional plane can be driven using arbitrary functions together with appropriate initial conditions. Additionally, dromion and RW solutions are also discussed. The dromion and RW patterns have an unstable amplitude and are reported to be stationary.

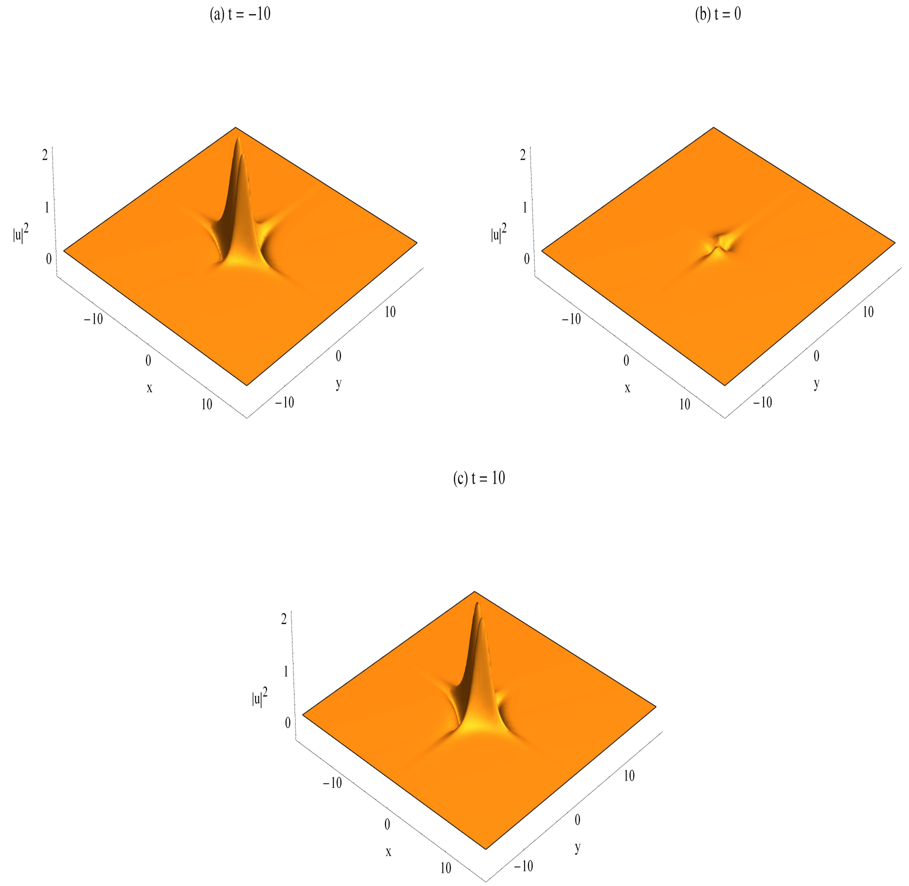

Fig. 4 Rogue waves for the component $|u|^2$ by using Eqs. (38) and (39) with the arbitrary constants $\alpha = 2.2$; $\beta = 2.5$; $\gamma = 1.75$; $p_1 = 1.95$; $p_2 = 3$; $p_3 = 1.75$; $p_4 = 2$ at t = -10; t = 0; t = 10.

Declarations

Conflict of interest/Competing interests

The authors state that the publication of this work does not pose a conflict of interest for them.

Availability of data and materials

This paper is exempt from data sharing since no datasets were created or evaluated during the research.

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