Physica A 492 (2018) 431–437

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Transport phenomena in intracellular calcium dynamics driven by non-Gaussian noises[☆]

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HIGHLIGHTS

- Calcium oscillation in cytosol shows positive, zero, and negative transport as p varies.
- Calcium in cytosol appears negative and zero transport as non-Gaussian noises increase.
- Calcium in both cytosol and calcium store occur negative, zero, and positive transport as correlation time of non-Gaussian noises varies.

ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 26 September 2017
Available online 31 October 2017

Keywords:
Intracellular calcium oscillation
Non-Gaussian noise
Cytosol
Calcium store

ABSTRACT

The role of non-Gaussian noises on transport characteristic of Ca^{2+} in intracellular calcium oscillation system driven by non-Gaussian noises is studied by means of second-order stochastic Runge–Kutta type algorithm. The statistical properties of velocity of cytosolic and calcium store's Ca^{2+} concentration are simulated. The results exhibit, as parameter p(which is used to control the degree of the departure from the non-Gaussian noise and Gaussian noise.)increases, calcium in cytosol shows positive, zero, and negative transport, but in calcium store always hold positive value. As non-Gaussian noises increase, calcium in cytosol appears negative and zero transport, and in calcium store appears positive transport. As correlation time of non-Gaussian noises varies, calcium in both cytosol and calcium store occur negative, zero, and positive transport.

1. Introduction

Ca^{2+} is an ubiquitous and versatile second messenger that transmits information through changes of the cytosolic Ca^{2+} concentration, namely, Ca^{2+} signaling pathway translates external signals into intracellular responses by increasing the cytosolic Ca^{2+} concentration in a stimulus dependent pattern. Specifically, the increasing of concentration can be caused either by Ca^{2+} entry from the extracellular medium through plasma membrane channels, or by Ca^{2+} release from the internal calcium store.

There are a variety of channels showing calcium-induced calcium release and a variety of models such [1–4] so far. In many studies on intracellular calcium oscillation(ICO) system, some phenomena have been found such as stochastic resonance [5,6], reverse resonance [6–8], oscillatory coherence [9], coherence resonance [7,10], resonant activation [11], calcium puffs [12], various spontaneous Ca^{2+} patterns [13], stochastic backfiring [14], dispersion gap and localized spiral

☆ This project are supported by the Science Research Fund of Yunnan Provincial Education Department (Grant No. 2016ZZX047), the National Natural Science Foundation of China (Grant No. 11305079 and Grant No. 11665014), the Natural Science Foundation of Yunnan Province (Grant No. 2015FB119).

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https://doi.org/10.1016/j.physa.2017.10.037
0378-4371/

waves [15], phase transition [16], stability transition [17], calcium wave instability [18], periodic square calcium wave [19] etc.

ICO is an interesting topic which has been intensively studied by Martin Falcke group [14,15,20–24]. They have studied a discrete stochastic model for calcium dynamics in living cells [20], spatial and temporal structures in intracellular Ca^{2+} dynamics caused by fluctuations [21], key characteristics of Ca^{2+} puffs in deterministic and stochastic frameworks [22], and exposure to low concentrations of inositol trisphosphate induces rapid clustering of inositol trisphosphate receptor Ca^{2+} release channels normally randomly distributed in endoplasmic reticulum/outer nuclear membranes [23]. At the same time, Matjaž Perc group [25–30] have studied ICO system, e.g., they have researched the role of regular calcium oscillations in protein activation [25] and calcium signaling in cell variability [26]. Among, Matjaž Perc group have found that noise and other stochastic effects indeed play a central role [27,28].

In these transmission processes of intracellular Ca^{2+}, there may be non-Gaussian noise [24]. Recently, we have studied ICO system driven by non-Gaussian noises [7,8,16,31,32], then found some phenomena such as noises enhance stability etc. However, the statistical properties of velocity of intracellular Ca^{2+} concentration have not been studied so far. Thus, in this paper, we study the statistical properties of velocity of Ca^{2+} concentration in ICO system driven by non-Gaussian noises.

2. The model for ICO with non-Gaussian noises

Taking into account same time delay τ in processes of active and passive transport of Ca^{2+} in a real cell, the Langevin equations of ICO system read as follows [7]:

$$d_t x = A_1(x; x_\tau, y_\tau) + B_1(x; x_\tau, y_\tau)\eta_1(t), \tag{1}$$

$$d_t y = A_2(x, y; x_\tau) + B_2(x, y; x_\tau)\eta_2(t), \tag{2}$$

with

$$A_1(x; x_\tau, y_\tau) = v_0 + v_1\beta_0 - v_2 + v_{3\tau} + k_f y_\tau - kx, \tag{3}$$

$$A_2(x, y; x_\tau) = v_{2\tau} - v_3 - k_f y, \tag{4}$$

$$B_1(x; x_\tau, y_\tau) = \sqrt{v_1^2\beta_0^2 + 2v_1\beta_0\lambda W + W^2}, \tag{5}$$

$$B_2(x, y; x_\tau) = \sqrt{\frac{v_{2\tau} + v_3 + k_f y}{V}}, \tag{6}$$

$$W(x; x_\tau, y_\tau) = \sqrt{\frac{v_0 + v_1\beta_0 + v_2 + v_{3\tau} + k_f y_\tau + kx}{V}}, \tag{7}$$

and

$$v_2 = \frac{V_2 x^2}{x^2 + k_1^2},\ v_3 = \frac{V_3 x^4 y^2}{(x^4 + k_2^4)(y^2 + k_3^2)}, \tag{8}$$

$$v_{2\tau} = \frac{V_2 x_\tau^2}{x_\tau^2 + k_1^2},\ v_{3\tau} = \frac{V_3 x_\tau^4 y_\tau^2}{(x_\tau^4 + k_2^4)(y_\tau^2 + k_3^2)}. \tag{9}$$

Here, x and y denote concentration of free Ca^{2+} of cytosol and calcium store in a cell, respectively. The rate v_2 and v_3 refer, respectively, to pumping of Ca^{2+} into the calcium store and to release of Ca^{2+} from store into cytosol in a process activated by cytosolic Ca^{2+}. $v_{2\tau}$ is v_2 with time delay, and $v_{3\tau}$ is v_3 with time delay. $W = W(x; x_\tau, y_\tau)$, $x_\tau = x(t-\tau)$, $y_\tau = y(t-\tau)$. λ denotes cross-correlation degree of internal and external noise before merger.

The noises $\eta_1(t)$ and $\eta_2(t)$ are considered as non-Gaussian noises which are characterized by the following Langevin equation [33]:

$$\frac{d\eta_i(t)}{dt} = -\frac{1}{\tau_1}\frac{d}{d\eta_i}V_{ip}(\eta_i) + \frac{\sqrt{2D}}{\tau_1}\xi_i(t),\ i = 1, 2 \tag{10}$$

where $\xi_i(t)$ is a standard Gaussian white noise of zero mean and correlation $\xi_i(t)\xi_i(t') = \delta(t-t')$. $V_{ip}(\eta_i)$ is given by

$$V_{ip}(\eta_i) = \frac{D}{\tau_1(p-1)}\ln[1 + \frac{\tau_1}{D}(p-1)\frac{\eta_i^2}{2}]. \tag{11}$$

Two noise sources $\eta_1(t)$ and $\eta_2(t)$ are statistically independent of each other, and the statistical properties of non-Gaussian noise $\eta_i(t)$ is defined as

$$\langle\eta_i(t)\rangle = 0, \tag{12}$$

$$\langle\eta_1(t)\eta_2(t')\rangle = 0, \tag{13}$$