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Astana IT University, Astana, Kazakhstan.

E-mail: mereyalbatyrova7139@gmail.com

ENERGY EVOLUTION EQUATION IN A NONLINEAR SPIN SYSTEM: DERIVATION AND NUMERICAL MODELING

Albatyrova Meray Babaykyzy — Master in Natural Sciences, teacher of School of Intelligent System, Astana IT University, Astana, Kazakhstan,

E-mail: mereyalbatyrova7139@gmail.com, ORCID ID: 0009-0002-8075-9393.

Abstract. This study investigates the numerical modeling of local energy evolution in a spin system governed by a dissipative generalization of the Landau–Lifshitz-type equation. Starting from a vector formulation that describes the dynamics of the spin field $S(x, t)$, we rigorously derive a corresponding scalar equation for the local energy density, expressed as $E(x, t) = \frac{1}{2} |S_x|^2$. This scalar representation proves to be a convenient analytical tool, as it effectively captures the spatiotemporal dynamics of the energy associated with evolving spin configurations while incorporating nonlinear interactions and dissipative mechanisms. The resulting equation reflects the interplay of multiple physical processes, including the contribution of an external scalar potential $u(x, t)$, convective energy transport, viscous-type diffusion, and curvature-induced dissipation modeled through the higher-order term $|S_{xxx}|^2$. Emphasis is placed on examining how variations in the dissipation coefficient and the structural properties of the external potential influence the qualitative and quantitative features of the energy distribution. To achieve this, we propose a scalar-field-based framework that enables direct observation of local energy evolution without resorting to solving the full nonlinear spin dynamics. Numerical simulations validate the approach, illustrating its effectiveness in identifying localized energy concentrations, tracing their propagation, and monitoring the decay of dissipative spin waves over time.

Keywords: soliton, local energy evolution equation, dissipative dynamics, nonlinear spin system, energy transport

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Astana IT University, Астана, Қазақстан.

E-mail: mereyalbatyrova7139@gmail.com

СЫЗЫҚТЫҚ ЕМЕС СПИНДІК ЖҮЙЕДЕГІ ЭНЕРГИЯ ЭВОЛЮЦИЯСЫНЫҢ ТЕНДЕУІ: ШЫҒАРЫЛУЫ ЖӘНЕ САНДЫҚ МОДЕЛЬДЕУ

Альбатырова Мерей Бабайқызы — жаратылыстану ғылымдарының магистрі, Зияткерлік жүйелер мектебінің оқытушысы, Astana IT University, Астана, Қазақстан,
E-mail: mereyalbatyrova7139@gmail.com, ORCID ID: 0009-0002-8075-9393.

Аннотация. Бұл жұмыста Ландау–Лифшиц типті тендеудің диссипативтік жалпылауымен сипатталатын спиндік жүйедегі энергияның локалдық эволюциясын сандық модельдеу қарастырылады. Спин өрісінің динамикасын $S(x, t)$ сипаттайтын векторлық тендеуден бастап, біз локалдық энергия тығыздығының скалярлық тендеуін аламыз, ол $E(x, t) = \frac{1}{2} |S_x|^2$ түрінде өрнектеледі. Мұндай скалярлық форма энергияның уақыт пен кеңістіктегі мінез-құлқын тиімді бейнелейді және бейсызық әсерлер мен диссипативтік өзара әрекеттесулерді қамтиды. Қорытынды тендеу бірнеше физикалық процестерді сипаттайды: сыртқы скалярлық потенциалдың $u(x, t)$ ықпалы, конвективтік энергия тасымалы, тұтқырлыққа ұқсас диффузия және спин өрісінің қисықтығымен байланысты энергия жоғалту, ол $|S_{xx}|^2$ мүшесі арқылы модельденеді. Зерттеуде диссипация коэффициентінің және сыртқы потенциалдың пішінінің өзгерістері энергияның кеңістіктік таралуына және уақыттық динамикасына қалай әсер ететініне ерекше назар аударылады. Бұл талдауды жеңілдету үшін толық спиндік динамиканы энергия эволюциясын қадағалауға мүмкіндік беретін скалярлық өріске негізделген тәсіл ұсынылады. Жүргізілген сандық модельдеулер әдістің тиімділігін көрсетіп, локалданған энергия шоғырларын анықтауға, олардың таралуын бақылауға және диссипативтік толқындардың әлсіреуін сипаттауға мүмкіндік берді.

Түйін сөздер: солитон, локалдық энергия эволюциясы тендеуі, диссипативтік динамика, бейсызық спиндік жүйе, энергия тасымалы

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Astana IT University, Астана, Қазақстан.

E-mail: mereyalbatyrova7139@gmail.com

УРАВНЕНИЕ ЭВОЛЮЦИИ ЭНЕРГИИ В НЕЛИНЕЙНОЙ СПИНОВОЙ СИСТЕМЕ: ВЫВОД И ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ

Альбатырова Мерей Бабайқызы — магистр естественных наук, преподаватель Школы интеллектуальных систем, Astana IT University, Астана, Казахстан,
E-mail: mereyalbatyrova7139@gmail.com, ORCID ID: 0009-0002-8075-9393.



Аннотация. В данной работе представлено исследование численного моделирования локальной эволюции энергии в спиновой системе, которая описывается диссипативным обобщением уравнения типа Ландау–Лифшица. Отталкиваясь от векторного уравнения, задающего динамику спинового поля $\mathbf{S}(\mathbf{x}, t)$, мы последовательно выводим скалярное уравнение для локальной плотности энергии, определяемой как $E(\mathbf{x}, t) = \frac{1}{2} |\mathbf{S}_x|^2$. Такая постановка задачи позволяет перейти от сложной многомерной динамики к более компактному описанию, удобному для анализа. Полученное уравнение отражает совокупность ключевых физических процессов: воздействие внешнего скалярного потенциала $u(\mathbf{x}, t)$, перенос энергии за счёт конвективных членов, диффузию вязкостного типа, а также потери энергии, связанные с кривизной спинового поля, которые моделируются через член $|\mathbf{S}_{xx}|^2$. Особое внимание уделяется влиянию коэффициента диссипации и формы внешнего потенциала на пространственно-временное распределение энергии. Для упрощения анализа разработан скалярный подход, который позволяет наблюдать эволюцию энергии без необходимости полного решения нелинейной спиновой динамики. Проведённые численные эксперименты подтверждают эффективность метода: он даёт возможность выявлять локализованные энергетические концентрации, проследить их распространение и фиксировать затухание диссипативных волн. Таким образом, работа демонстрирует потенциал предложенного подхода как инструмента для дальнейших исследований нелинейных спиновых систем.

Ключевые слова: солитон, уравнение эволюции энергии, энергия, спин, нелинейная спиновая система

Introduction. Solitons are a remarkable class of nonlinear wave solutions that maintain their shape and speed over long distances and periods of time, despite the presence of dispersion and nonlinearity. Originally discovered in shallow water wave systems by John Scott Russell in the 19th century, solitons have since been identified in a wide range of physical systems, including optical fibers, plasmas, condensed matter, and spin chains, as demonstrated in the works of Ablowitz, M. J., Segur, H. (1981) and Dauxois, T., Peyrard, M. (2006). Unlike ordinary wave packets, which typically spread out and dissipate, solitons exhibit particle-like behavior - they can collide, pass through each other, and re-emerge without loss of identity. In this sense, solitons share striking similarities with real physical particles, particularly in their ability to preserve structural integrity over time and space, as discussed in the investigations of Manton, N., Sutcliffe, P. (2004).

The study of solitons is important not only from a theoretical standpoint but also due to their wide range of applications. In nonlinear optics, solitons enable robust data transmission in optical fibers which is shown in Agrawal, G. P. (2019), in condensed matter physics, they model topological excitations in spin systems in Lakshmanan, M. (1977) and in cosmology, they appear in models of domain walls and early-universe defects Vilenkin, A., Shellard, E. P. S. (1994). The ability to describe long-

lived, localized energy transport makes solitons a powerful tool for understanding and controlling complex dynamical systems.

In this work, we investigate soliton-like energy behavior within a one-dimensional spin field governed by a nonlinear, dissipative evolution equation. Rather than tracking the full vector field $S(x,t)$, we focus on the evolution of the local energy density $E(x,t) = \frac{1}{2} |S_x|^2$, derived from the underlying spin dynamics. To analyze this energy flow, we introduce a framework that allows us to study how energy propagates, dissipates, and localizes without solving the full vector system.

This method is particularly useful in systems with dissipation or external interactions, where direct interpretation of the vector field becomes challenging. By analyzing the scalar energy profile, we gain intuitive and quantitative insight into how energy packets evolve over time, whether they spread out like diffusive waves or retain localized features resembling solitons. Studying such behavior helps identify stable, particle-like energy modes in nonlinear media and improves our understanding of energy transport mechanisms in spin-based systems.

Materials and methods. In this work, we define the local energy density of a spin field as

$$E(x,t) = \frac{1}{2} |S_x|^2 = \frac{1}{2} (S_x S_x)$$

Here, $S(x,t)$ is a unit vector field representing spin orientation, and S_x is its spatial derivative. This formulation describes how strongly the field configuration changes across space and is widely used in the physics of magnetism and nonlinear field theory.

Such an energy density naturally arises in the nonlinear sigma model (NL σ M), a widely studied framework for modeling continuous spin fields. In these models, the Lagrangian typically takes the form

$$\mathcal{L} = \frac{1}{2} \partial_\mu \partial^\mu S$$

where the dynamics of the spin field are constrained by the condition $|S| = 1$. The spatial part of this Lagrangian corresponds directly to the energy density we use, and this form has become a standard in continuum spin models. This approach is supported by foundational studies, such as those by Assa Auerbach (1988), which highlight the role of spatial gradients of spin fields in determining energetic and dynamical properties of magnetic systems. Focusing on the scalar energy density rather than the full vector field provides clearer insight into dissipation, localization, and transport mechanisms in nonlinear spin environments.

We consider our modified model in the following form:

$$S_t - S \wedge S_{xt} - u S_x = v S_{xx} \quad (1)$$

$$u_x + \frac{1}{2} (S_x^2)_t = -\gamma u \quad (2)$$

In this system, the first equation governs the dynamics of the spin vector field $S(x,t)$, where v is the dissipation coefficient and \wedge wedge denotes the vector product. This

equation describes how the spin field evolves in both space and time under the influence of external interactions and internal curvature. While the second equation is a scalar equation that models the evolution of the auxiliary field $u(x,t)$, which interacts with the spin field through its spatial gradient and energy density.

We introduced a definition for the local energy density and then aimed to derive an equation describing its time evolution, specifically the partial derivative $\frac{dE}{dt}$, based on our system. The motivation behind this step is to study how the energy associated with the spin field changes over time and to better understand the behavior of wave-like structures within the system. By tracking the evolution of the local energy density, we can analyze where and when energy tends to increase, and in which regions it dissipates or decays. This information is crucial for identifying zones of wave amplification versus attenuation, especially in nonlinear and dissipative media. Solving this scalar equation rather than the full vector field equations provides a clearer and more intuitive picture of the underlying energy transport processes. It simplifies the analysis while preserving essential features of the original spin system. It allows us to follow the dynamics of energy concentration, recognize patterns of dissipation, and detect localized structures that may behave like solitons. Thus, the evolution equation for $E(x,t)$ becomes a powerful tool for understanding how energy flows through the system and how different parameters influence this process.

$$E(x, t) = \frac{1}{2} (\mathbf{S}_x \mathbf{S}_x), \tag{3}$$

It follows from equation (3) that

$$\frac{dE}{dt} = \mathbf{S}_x \mathbf{S}_{tx} \tag{4}$$

We can represent our system (1) in the following explicit form:

$$\mathbf{S}_t = \mathbf{S} \wedge \mathbf{S}_{xt} + u \mathbf{S}_x + v \mathbf{S}_{xxx} \tag{5}$$

We begin by substituting equation (5) into equation (4),

$$\frac{dE}{dt} = u \mathbf{S}_x \mathbf{S}_x + u \mathbf{S}_x \mathbf{S}_{xxx} + v \mathbf{S}_x \mathbf{S}_{xxx}$$

while expressing all scalar products in terms of the energy density $E(x,t)$. The following identities are used to rewrite the nonlinear terms:

$$\mathbf{S}_x \mathbf{S}_x = 2E,$$

$$\mathbf{S}_x \mathbf{S}_{xxx} = \frac{dE}{dx},$$

$$\mathbf{S}_x \mathbf{S}_{xxx} = \frac{d^2 E}{dx^2} - \mathbf{S}_{xx} \mathbf{S}_{xx}.$$

These relationships allow us to express the scalar projections of the spin derivatives purely in terms of the energy density and its spatial derivatives. As a result, we obtain equation (3) in a new form, which we refer to as equation (6).

$$\frac{dE}{dt} = uE + u \mathbf{S}_x \frac{dE}{dx} + v \left(\frac{d^2 E}{dx^2} - \mathbf{S}_{xx} \mathbf{S}_{xx} \right) \tag{6}$$

This equation describes the time evolution of the energy density $E(x,t)$ for the spin system originally given in system (1). The reformulated version isolates the effects of the external field, convective transport, diffusion, and dissipation in a scalar framework, making it significantly more convenient for analysis and numerical simulation.

Results

The model successfully captures the behavior of energy in a nonlinear spin system: local wave structures dissipate and decay over time, as expected from the governing equation. The applied approach allows for precise tracking of where and when energy vanishes, without the need to solve the full vector equation for $S(x,t)$

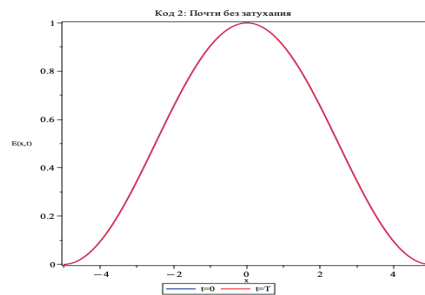


Figure 1. Nearly No Dissipation

Figure 1 illustrates the scenario “Nearly No Dissipation”, in which the system parameters are specifically chosen to eliminate energy loss. With zero viscosity $\nu = 0$ and $|S_{xx}| = 0$, no external potential field, and no curvature-induced dissipation, the energy distribution remains unchanged over time. The complete overlap of the energy profiles $E(x,0)$ and $E(x,T)$ demonstrates the stationarity of the solution, making this regime an idealized analog of a non-interacting soliton. We consider a regime in which energy is preserved over time without significant dissipation. The system parameters are chosen specifically to eliminate the influence of dissipative mechanisms and to demonstrate the quasi-stationary behavior of the energy profile.

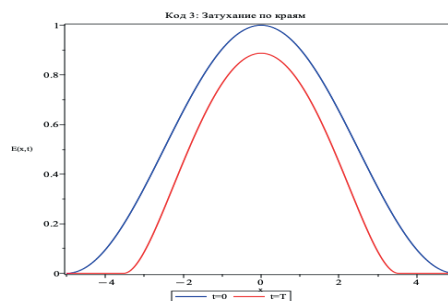


Figure 2. Dissipation near the boundaries

Figure 2 illustrates the results of modeling local energy density in a spin system under the condition that dissipation is spatially dependent and primarily concentrated

near the boundaries of the domain. The parameters were chosen to ensure that energy remains preserved in the central region while gradually decaying at the edges. The curvature-dependent dissipation term is defined as $|S_{xxx}| = \sin^2\left(\frac{\pi x}{L}\right)$ which stretched over an interval of length L and vanishes near the center and increases toward the boundaries. The viscosity coefficient is set to $\nu = 0.1$, and the external field is absent, $u(x) = 0$. The initial energy profile is given by $E(x, 0) = \cos^2\left(\frac{\pi x}{L}\right)$, which has a maximum at the center and zeros at the domain edges. As the simulation progresses, the energy profile maintains its shape near the center while diminishing at the boundaries, as evidenced by the comparison between the curves at $t = 0$ (blue) and $t = T$ (red). This behavior reflects localized dissipation and demonstrates how energy becomes concentrated in the interior of the domain, forming a quasi-stable structure while energy is lost near the periphery.

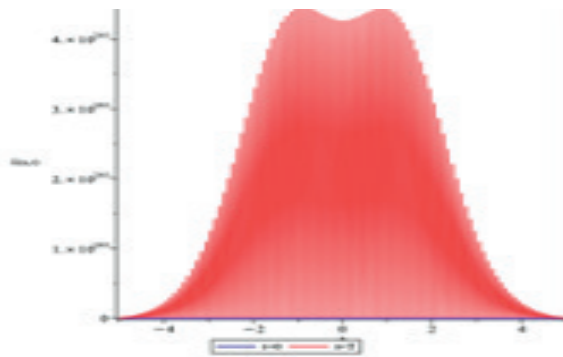


Figure 3. Strong Dissipation

The graph presents the behavior of local energy density in the numerical experiment titled “ Strong Dissipation”. The goal of this scenario is to investigate how energy rapidly dissipates throughout the domain under the influence of pronounced dissipative mechanisms. The system parameters were chosen as follows: the viscosity coefficient was set to $\nu = 0.5$, which is relatively high to ensure significant energy loss, and the curvature-related dissipation term was defined as $|S_{xxx}| = \text{const}$, meaning dissipation is uniform across the entire spatial domain. The initial energy profile was defined by a Gaussian function: $E(x, 0) = \exp(-x^2)$ localized around the center and decaying toward the edges. The external scalar field was set as $u(x) = \sin\left(\frac{\pi x}{L}\right)$, with its derivative given by $u'(x) = \frac{\pi}{L} \cos\left(\frac{\pi x}{L}\right)$. However, instead of the expected decay, the numerical simulation displays an unexpected and unphysical exponential growth in the energy profile. The initially smooth and localized distribution remains near zero at $t = 0$ (blue curve), while the final state at $t = T$ (red curve) rises sharply and forms a jagged, spike-like structure. This behavior is a clear indication of numerical instability, most likely resulting from an inappropriate balance between the spatial and temporal resolution in relation to the chosen viscosity. Such an outcome emphasizes the necessity of carefully selecting discretization parameters and employing stable numerical schemes when modeling nonlinear dissipative systems.

Discussion

The numerical results obtained in this study provide valuable insight into the behavior of energy in a one-dimensional spin system under different dissipation conditions. The approach proved effective for monitoring the evolution of energy density without solving the full vector equation for the spin field $S(x,t)$. This simplifies the computational process and allows for clearer interpretation of the system's dynamics.

By analyzing different dissipation patterns including uniform dissipation across the domain, dissipation localized near the boundaries, and minimal or no dissipation it becomes evident that each configuration leads to distinct energy dynamics. Uniform dissipation results in rapid energy decay throughout the entire region. When dissipation is spatially localized at the boundaries, the system exhibits stable energy retention in the center while losing energy at the edges. In the absence of dissipation, the energy profile remains quasi-stationary, with minimal changes over time.

One of the strengths of this approach lies in its generality and flexibility. The method can be adapted to other field models and extended to higher-dimensional systems. However, the study also has limitations: the model is restricted to one spatial dimension and does not account for stochastic effects or microscopic interactions that may be significant in real physical systems. Moreover, cases with high dissipation levels require special attention to numerical stability, and may benefit from more advanced time-stepping methods.

Overall, the findings show that spatially controlled dissipation has a significant impact on how energy moves and concentrates in a system. The simplified scalar model used in this study proves to be a useful tool for gaining insights into the behavior of more complex nonlinear systems.

Solitons, in general, are a key concept in physics. They describe how energy can remain stable and localized while moving through a nonlinear medium, which is important for understanding both classical and quantum systems.

These stable, nonlinear waves are interesting because they behave like both waves and particles. That unique dual nature makes them a promising model for describing elementary particles. For example, in Boris Slavin's article *Soliton Interpretation of Quantum Theory*, he suggests that particles like the electron might actually be soliton solutions of nonlinear equations. In particular, these are the Maxwell equations, where the charge and current densities are expressed through quadratic combinations of electric and magnetic field strengths.

Unlike the traditional approach, where the wave function is treated merely as a tool for calculating probabilities, the soliton interpretation assigns it a physical meaning. In this view, the complex wave function represents an electromagnetic wave: the real part corresponds to the electric field, and the imaginary part to the magnetic field. This concept allows for a synthesis between the Copenhagen interpretation and Bohm's hidden variable theory.

A defining feature of solitons is their ability to maintain shape while propagating and interacting, due to their "transparency" to specific waveforms. Using the inverse scatter-

ing transform (IST) method, analytical soliton solutions can be obtained-much like how eigenfunctions are used in quantum theory to describe particle states.

Thus, in this framework, quantum equations are interpreted not as governing the dynamics of particles directly, but as boundary conditions that determine the existence of soliton solutions. This perspective provides a new understanding of wave-particle duality and offers a way to connect quantum mechanics with classical electrodynamics in its nonlinear form.

Conclusion

This study presents a comparative analysis of energy evolution under three distinct dissipative regimes in a one-dimensional spin system: strong dissipation, boundary-localized dissipation, and near-zero dissipation. Each scenario demonstrates a unique pattern of energy decay or persistence, governed by the choice of parameters such as viscosity, curvature-related loss, and external field structure $u(x)$. The strong dissipation case exhibits rapid, uniform energy decay across the domain, while the boundary-localized model reveals sustained energy in the center and loss at the edges. In contrast, the near-zero dissipation regime maintains a quasi-stationary energy profile throughout the simulation time.

The ability to selectively control dissipation both spatially and temporally enables the modeling of various physical systems in which long-lived localized excitations or wave decay play a critical role. For example, such mechanisms are relevant in magnetic materials (Auerbach, 1994), optical solitons in fiber networks (Agrawal, 2019), and condensed matter systems with topological structures that resist decay (Manton & Sutcliffe, 2004). Furthermore, the proposed way of solving the problem provides an efficient means of tracking energy redistribution without the need to solve the full vector dynamics. This makes it a valuable tool for modeling nonlinear spin systems, metamaterials, and even theoretical models in cosmology and field theory (Vilenkin & Shellard, 1994).

Overall, the results highlight the importance of controlling and understanding dissipative behavior in nonlinear media, and provide a computational framework that can be extended to explore soliton stability, energy trapping, and engineered wave decay in various applications.

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