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CHAOS AND COHERENCE IN CLASSICAL ONE-DIMENSIONAL MAGNETS

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Abstract

Numerical studies are reported for one-dimensional classical ferromagnetic chains with easy-plane anisotropy and various applied magnetic fields and damping terms. The possibility of temporal chaos is very sensitive to the configuration of anisotropy and magnetic fields. It is found that large amplitude spatial structures can dominate long-time attractors and compete with temporally chaotic tendencies.

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It has become widely appreciated that soliton-like coherent structures are important excitations and intrinsic defect patterns in condensed matter materials, including magnetic systems and especially in low spatial dimensions [1]. For many problems of current interest it is essential to examine new phenomena which can dominate the physics in non-equilibrium-nonlinear regimes. For instance, in view of the rising interest in nonlinear dynamical systems, one natural question to ask is: how do strong tendencies toward spatial coherence compete against strong perturbations which might be expected to promote spacetime complexity (including "chaos)? This is a very general concern in many-degree-of-freedom systems including plasmas, hydrodynamics, combustion and cellular automata. The controlled experiments possible on well-characterized, low-dimensional solid-state materials afford important vehicles to study dynamical systems questions which cross these interdisciplinary boundaries.

Studies of classes of partial differential equations modeling low-dimensional solid-state materials (including the sine-Gordon and nonlinear Schrödinger equations [2,3]) have revealed some intriguing general phenomena. For example, in the presence of dissipation and a.c. driving fields, it has been found that spontaneous pattern formation, low-dimensional chaos and coexisting coherence and chaos typically are intimately connected. We have found that this scenario also extends to classical, dissipative, easy-plane ferromagnetic chains in the presence of various combinations of a.c. and d.c. magnetic fields. Note that the order parameter here is two-dimensional.

Including Landau-Lifshitz phenomenological damping (strength ε), the spin ($\{\vec{S}_n\}$) equation of motion we have considered is [4]

$$\dot{\vec{S}}_n = \vec{S}_n \times \vec{G}_n \quad ; \quad \vec{G}_n = \vec{F}_n - \frac{\varepsilon}{S}(\vec{S}_n \times \vec{F}_n)$$

$$\vec{F}_n = J(\vec{S}_{n-1} + \vec{S}_{n+1}) + g\mu_B\vec{B} - 2AS_n^z\hat{z} \quad . \qquad (1)$$

Here, $\vec{F}_n$ derives from a conventional nearest-neighbor Heisenberg model with local easy-plane symmetry-breaking ($A > 0$) and a general applied magnetic field ($\vec{B} = \vec{B}_{dc} + \vec{B}_{ac}\sin\omega t$). Simulations were performed both for an individual spin and for a periodic ring of 150 spins, in each case for the following five field configurations: (i) $\vec{B} = B_{ac}\hat{z}$ ($\perp$ easy plane); (ii) $\vec{B} = B_{ac}\hat{x}$ (i.e. in easy plane); (iii) $\vec{B} = B_{dc}\hat{x} + B_{ac}\hat{z}$; (iv) $\vec{B} = B_{dc}\hat{x} + B_{ac}\hat{x}$; and (v) $\vec{B} = B_{dc}\hat{x} + B_{ac}\hat{y}$. Time series were analyzed with several diagnostics, including power spectra, spatial average of magnetization, phase space, Poincaré sections, space and time correlation functions, and correlation dimensions. Several classes of initial data were used including (for the multispin chains) symmetric pulse profiles and random profiles. To explore possible applications to $CsNiF_3$ we used parameters $A/J = 0.19$, $g = 2.4$, $\varepsilon = 0.1$, driving field strengths from 0 to 50 kG and a driving frequency of 25 GHz.

Complete results will be published elsewhere [4]. Here we report a few general features and illustrative examples.

For both single and multispin cases we have observed <u>only</u> temporally periodic behavior for $\vec{B} = B_{ac}\hat{z}$ or $\vec{B} = B_{dc}\hat{x} + B_{ac}\hat{y}$ (here $B_{dc} = 5$ kG). Chaos is possible for all other field configurations, most easily for $\vec{B} = B_{ac}\hat{x}$ or $\vec{B} = B_{dc}\hat{x} + B_{ac}\hat{x}$. As for other single oscillators [5], a rich range of attractors is observed for the single spin as $B_{ac}\hat{x}$ is varied, including numerous subharmonics.

The field configuration $\vec{B} = B_{dc}\hat{x} + B_{ac}\hat{z}$ is closest to the problem of a driven, damped sine-Gordon chain, studied in detail elsewhere [2], and frequently invoked as an approximate model for easy-plane ferromagnetic chains [6]. Assuming small out-of-easy-plane motions, the in-plane angle ϕ can be shown to be governed (in a continuum limit) by

$$\phi_{xx} - \phi_{tt} = \sin\phi + \alpha\phi_t + \Gamma \sin\omega t \quad , \qquad (2)$$

where x, t, α and Γ are effective sine-Gordon parameters determined by the magnet parameters [4]. Direct simulations of the full magnetic chain with B_{dc} = 5 kG show a chaotic transition at $B_{ac} \simeq 29$ kG (other parameters). In the notation of eq. (2) this corresponds [4] to $\alpha \simeq 0.3$ and $\Gamma \simeq 0.8$ -- this is consistent with chaos being slightly easier in the magnetic system than the sine-Gordon approximation [2].

For the multi-spin cases showing non-trivial behavior ((ii), (iii), (iv) above), a rich variety of space-time attractors are observed. Spatially flat, time periodic attractors are found for small B_{ac} and temporal chaos is always accompanied by large amplitude permanent spatial patterns -- kinks, antikinks, breathers, etc. [2] -- which may have the lowest spatial symmetry on the periodic ring (period-1) or higher symmetry (e.g., period-½). As in many other driven, damped partial differential equations [2,3], chaos is typically found to be low-dimensional and frequently develops by breaking the higher spatial symmetry of pre-chaotic quiescent regimes -- <u>without</u> destroying the elementary coherent structures. An example is shown in the figure for $\vec{B} = B_{ac}\hat{x}\sin\omega t$, with ω = 25 GHz, B_{ac} = 4 kG and 5 kG, and random initial data. For B_{ac} = 5 kG, the attractor is simply periodic in time and period-½ in space (Fig. 1a). However, with B_{ac} = 4 kG the attractor is chaotic (intermittent) -- during approximately periodic laminar time intervals the spatial structure is a smooth low-amplitude wave (see the early time in Fig. 1b), whereas during the chaotic bursts the spatial structure is a broken period-½ pattern (see the later time in Fig. 1b and compare Fig. 1a).

The combination of driving frequencies and amplitudes reported here are too extreme for practical accessibility in $CsNiF_3$. However, the variety of space-time complexity which is possible suggests that numerical and experimental studies of low-dimensional magnets can shed light on important general dynamical systems issues.

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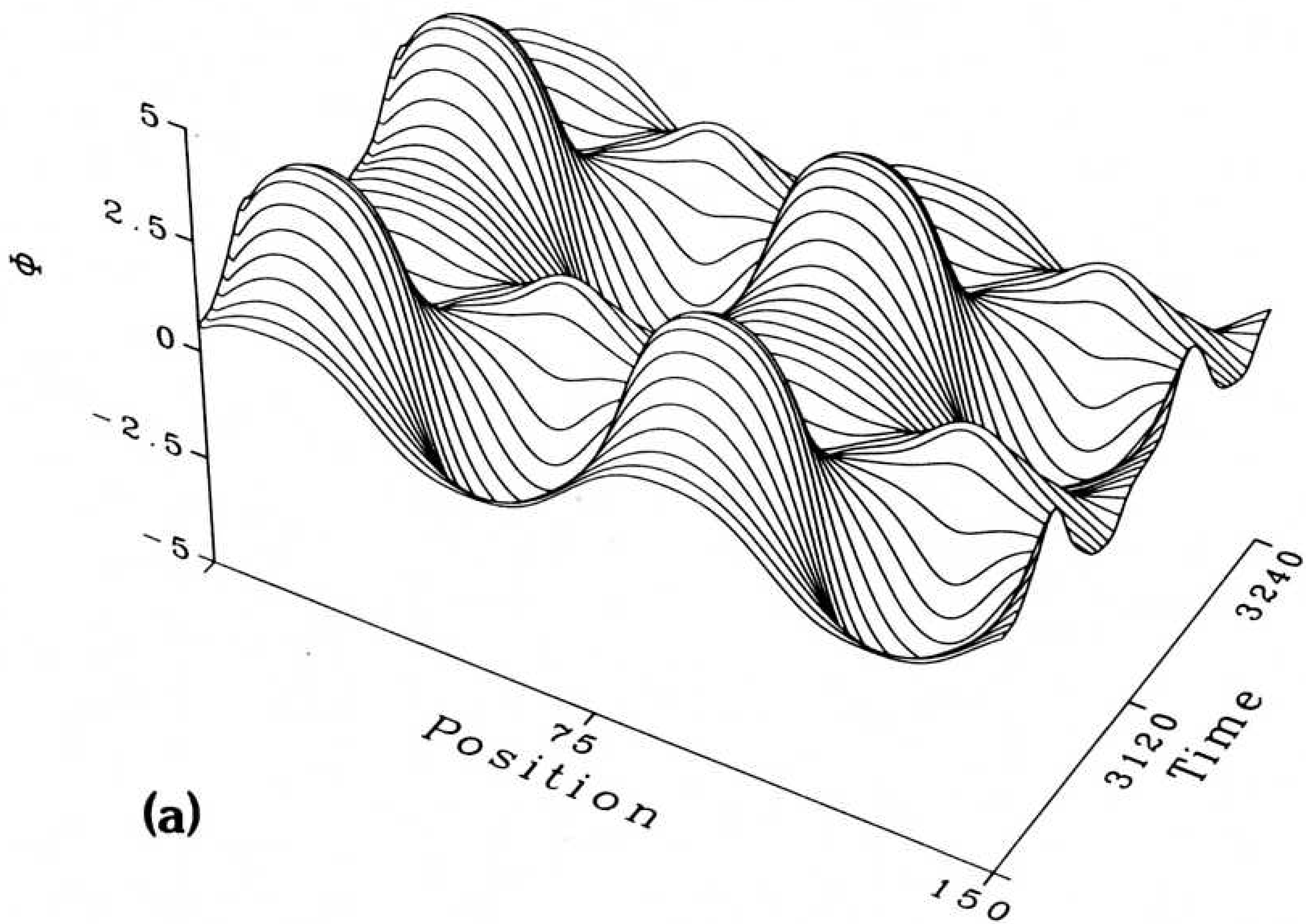
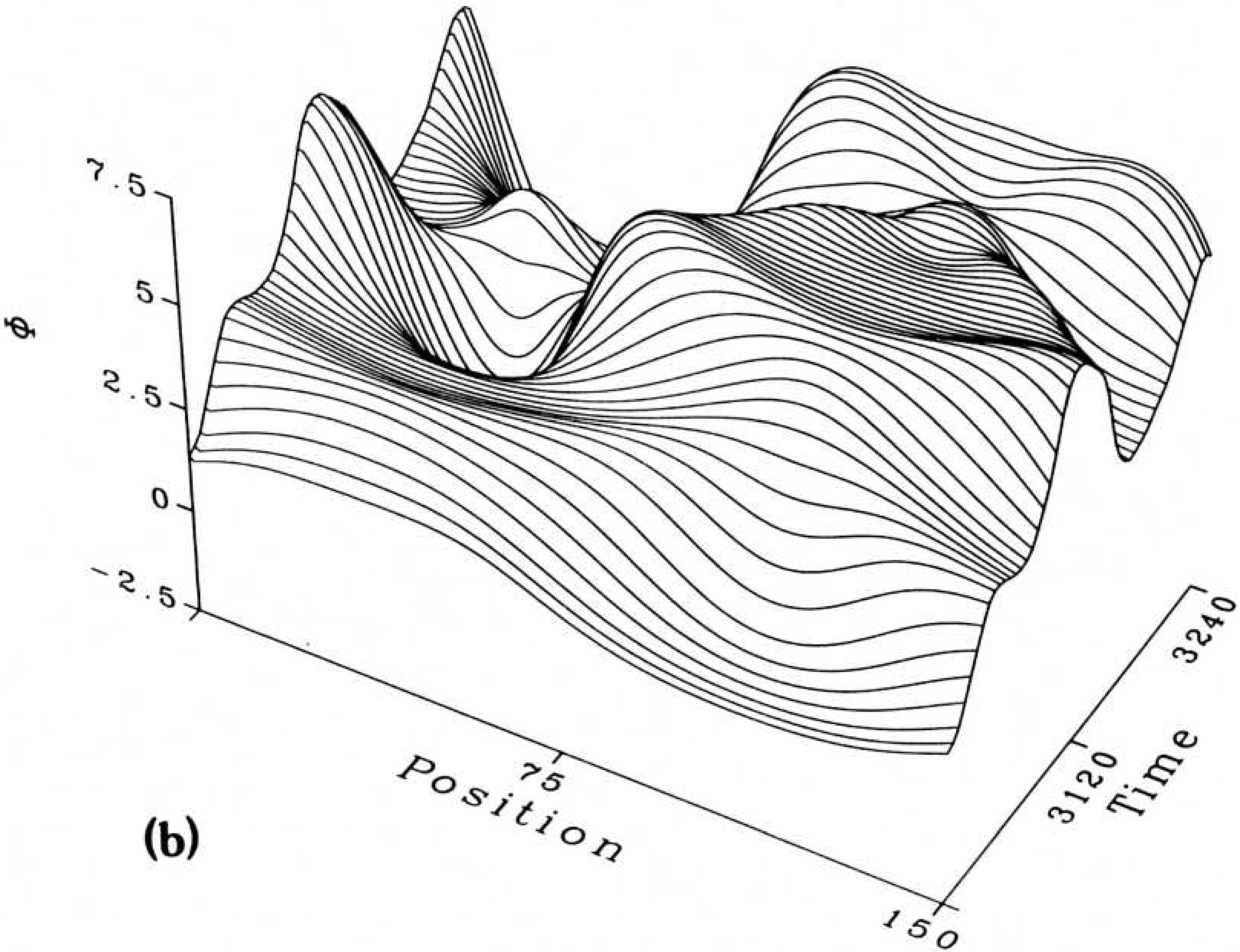
Figure Caption

Space-time evolution of the in-plane angle ϕ for the easy-plane ferromagnetic chain with 150 spins, periodic boundary conditions and random initial data [4]. (Other parameters are given in the text.) Evolution through two driver periods is shown: (a) B_{ac} = 5 kG and the attractor is simply periodic in time but spatially periodic-½; (b) B_{ac} = 4 kG and the attractor is chaotic with intermittency between smooth standing wave structures and chaotic kink-antikink dynamics.



(a)



(b)