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MAGNETIC SOLITONS

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Solitons and localized dissipative structures are the most natural and well-observed manifestation of nonlinear dynamics of energetically open systems at all scales ranging from the quantum structures to astrophysical objects. Depending on the system parameters and an adequate scaling, these phenomena are successfully described by the equations of Korteweg de Vries (KdV), Gross–Pitaevskiy (GP), Kadomtsev–Petviashvili (KP), Ginzburg–Landau (GL), and their modifications. In this paper we discuss formation and dynamics of magnetic solitons observed in the solar atmosphere. The MHD theory of magnetic solitons and results of quantitative analysis of observational data are presented.

The Sun as a star that seems from a distance as a weakly magnetized, 1 Gs neat dipole, is in fact an extremely complex magnetic body. At any moment of time, constantly changing, randomly magnetized solar atmosphere is pierced by unevenly spaced bundles of thin magnetic flux tubes [1–3]. Tightly spaced, they form sunspots and active regions with magnetic field strength of 2000–4000 Gs. Outside sunspots, the 90 % of the solar surface is covered by widely spaced magnetic flux tubes of mixed polarities that cover the Sun as pepper and salt. The magnetic field in the individual flux tubes varies from 100 to 1500 Gs. And at all scales, from the surface to the corona and solar wind, the magnetic fields have a pronounced filamentary structure.

Embedded in highly dynamic environment, the system of thin magnetic flux tubes and associated unsteady mass flows, all being subjected to gravity and radiative losses, forms a typical energetically open system with vigorous dynamics. This applies to virtually all the local processes in the solar atmosphere providing thus the most natural conditions for the formation of various dissipative structures.

In this paper, we discuss some aspects of nonlinear dynamics of magnetic flux tubes in a dissipative medium with dispersion. Although similar conditions are valid throughout entire atmosphere of the Sun we choose here, as an example, the sunspot environment.

Sunspots and their penumbrae consist of an "uncombed" system of thin magnetic flux tubes. Directed vertically upward in the umbra — the center of the sunspot, flux tubes gradually deviate toward periphery forming penumbra — an umbrella-like ensemble of flux tubes (Fig. 1). These areas exhibit a great variety of mass flows, magnetic flux emergence and cancellations. Some of the most spectacular phenomena are associated with a Moving Magnetic Features (MMFs), streaming continuously out of penumbra towards its periphery. Along the line of sight, they are seen as opposite polarity compact bipoles traveling together. Exhibiting all the properties of evolutionary solitons, these kinked formations are ubiquitous: they are observed around any given sunspot at any moment of time [4–9].

Thin magnetic flux tubes comprising umbra and penumbra and buffeted by surrounding convective motions are subject of various oscillations. The most readily excited is a kink mode with the azimuthal wave number $m = \pm 1$. In nonlinear regime, in presence of dispersive and dissipative effects, kink oscillations of flux tubes are described by a KdV–Bürgers equation [7, 10]. Its analytical and numerical solutions provide several regimes of the evolutionary solitons, which are expressed in directly observable parameters. This fact allows reliable quantitative analysis and comparison with observations.

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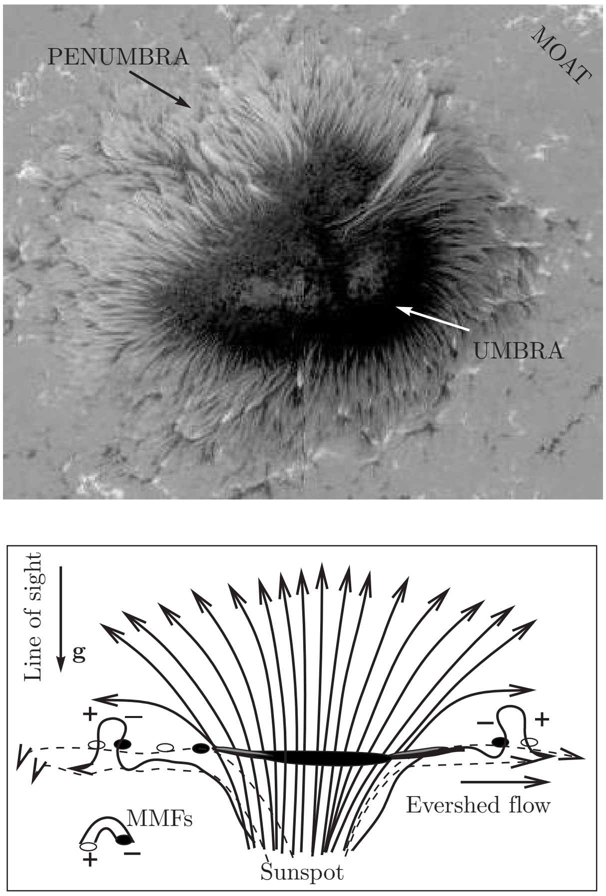

Fig. 1. Top: longitudinal (line-of-sight) magnetogram of a sunspot. Field of view is 12×16 Mm^2. Negative magnetic field is in black, positive is in white. Note numerous black-and-white pairs everywhere in penumbra and farther outward. These compact bipoles are footpoints of magnetic solitons. Bottom: cartoon visualizing a vertical cut of sunspot with kinked penumbral flux tubes with their bipolar footpoints seen along the line of sight

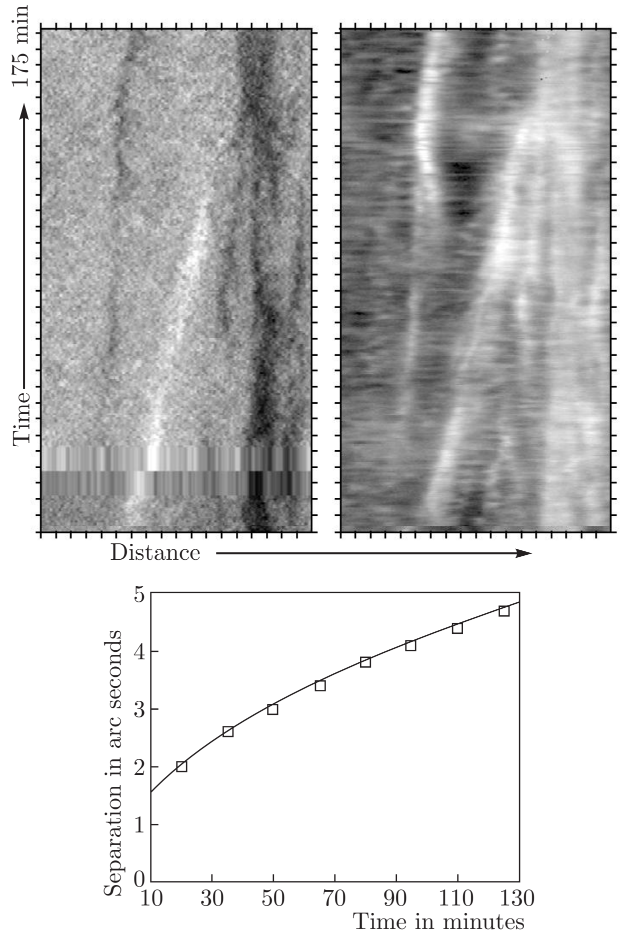

Fig. 2. An exemplary magnetic soliton. Upper panels show motions of the negative and positive soliton footpoints from magnetogram movie (left) and their imprint in the overlying chromosphere from Ca II K movie (right); time tick marks are 5 min, spatial tick marks are arcsec (about 725 km). Lower panel is the time variation of the width of a soliton. Squares indicate the observed values, and the solid line is a theoretical fit showing a perfect match of theory and observations

The most important is to study temporal variability of observed processes. For this reason, a special procedure, called space-time cuts (slices) has been developed for application to data compiled in movies [11]. This procedure allows one to follow motions of any bright and dark patches lying along the cut made on one of the movie snapshots. Example of such a procedure is shown in Fig. 2. The co-aligned time series for the magnetograms (left panel) and Ca II K-line filtergrams (right panel) have been compiled in movies. The 3 Å Ca II K filter reflects the chromospheric temperatures at about $2 \cdot 10^4$ K appearing thus as bright tracks along footpoints of traveling soliton.

Hence, what we see in Fig. 2 is an examplary soliton traveling for hours with slowly varying width of soliton — the distance between the footpoints of a kink.

The behavior of this soliton, as all the observed ones, strictly obeys the laws of evolutionary solitons. For example, comparison of the measured separation of soliton footpoints as a function of time with the theoretical curve (Fig. 2, lower panel) reveals an excellent match.

The physical processes responsible for the formation, evolution, and decay of sunspots and active regions are strongly dominated by ever emerging small magnetic fluxes, including the MMFs. These ubiquitous features play a significant role in energetics of sunspots and overlying corona [12]. The modern multiwavelength observations with high cadence and high resolution call for further studies of these phenomena and development of predictability tools.

This said, I would be happy to prepare the upcoming results on this subject for the next issue of the JETP to be dedicated to the 90th anniversary of Lev Pitaevskiy. If, of course, I'll be again invited to participate in that issue.

Now, I would like to thank the editorial board of JETP and, in particular, Sasha Andreev and Igor Fomin for the honor given to me to present a paper to this issue and serve as a guest editor.

I am immensely grateful to Lev Pitaevskiy for everything he has done for me. In the first place, he taught me how to do lengthy calculations, to see behind them a simple order of things, and never get bored of it.

After my diploma supervised by Isaak Khalatnikov, I began work on what was to be my PhD thesis. Here my adviser was Alexei Abrikosov. And everything went well in this amazing institute with its remarkable people and beautiful science. One day, Lev Pitaevskiy put forward some problem and suggested that I think about it. I did not think much: the problem was challenging and captivating, and I ventured. Abrikosov did not object. And that was it. Lev and I did the work, and the paper submitted to the JETP on August 3, 1965 was published in January 1966. Soon after, Abrahams and Tsuneto in their 17-page paper entitled "Time Variation of the Ginzburg–Landau Order Parameter" [13], wrote: "*Note added in proof.* Using a slightly different method, M. P. Kemoklidze and L. P. Pitaevskiy [14] have derived results similar to ours for the neutral pure superconductor at absolute zero". In February 1967, I defended my thesis based on works done under the supervision of Pitaevskiy. Moreover, thanks to him, I became a staff member in Kapitsa's Institute. Ever since and throughout all these years that have changed countries and added us age, I cherish our friendship. And every year we have been saying kind words to each other at least and necessarily on January 18th.

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