Magnetohydrodynamic Relaxation in Astrophysical Plasmas

A Thesis

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MOHANLAL SUKHADIA UNIVERSITY

in the

Faculty of Science

By

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DECLARATION

I, **Mr. Sanjay Kumar**, S/o Mr. Fakir Chand, resident of C-2, USO staff quarters, Badi road, Udaipur-313001, hereby declare that the research work incorporated in the present thesis entitled, **"Magnetohydrodynamic Relaxation in Astrophysical Plasmas"** is my own work and is original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma. I have properly acknowledged the material collected from secondary sources wherever required. I solely own the responsibility for the originality of the entire content.

Date:

Sanjay Kumar
(Author)

CERTIFICATE

I feel great pleasure in certifying that the thesis entitled, **"Magnetohydrodynamic Relaxation in Astrophysical Plasmas"** embodies a record of the results of investigations carried out by **Mr. Sanjay Kumar** under my guidance. He has completed the following requirements as per Ph.D regulations of the University.

(a) Course work as per the university rules.

(b) Residential requirements of the university.

(c) Regularly submitted six monthly progress reports.

(d) Presented his work in the departmental committee.

(e) Published minimum of one research papers in a referred research journal.

I recommend the submission of thesis.

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Countersigned by

Head of the Department

To

My Family

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ABSTRACT

The astrophysical plasmas in general, and the solar corona in particular, are described by the non-diffusive limit of magnetohydrodynamics. The reason for the achievement of this limit is the large length scales and high temperatures inherent to such plasmas, making magnetic Reynolds number ($R_M = vL/\lambda$, in usual notations) extremely high. These high R_M plasmas satisfy the Alfvén theorem of flux-freezing, resulting in tying magnetic field lines with fluid parcels during an evolution. In such plasmas, small scales in magnetic field, or equivalently current sheets develop spontaneously in accordance with the Parker's magnetostatic theorem. These current sheets are the locations where the plasma becomes locally diffusive because of a local reduction in R_M. The consequent magnetic reconnections convert the magnetic energy into heat and kinetic energy of mass outflow along with a topological rearrangement of magnetic field lines. With reconnections, the current sheets decay and magnetic field lines frozen with the mass outflows push onto other magnetic field lines and, under favorable conditions may lead to secondary current sheets and second generation reconnections. These reconnections are expected to repeat in time until the plasma relaxes to a terminal state characterized by an allowable minimum of the magnetic energy. Consequently, a scenario is proposed where the magnetohydrodynamic relaxation, maintained by the repeated magnetic reconnections, provides an autonomous mechanism which governs the creation and dynamics of coherent structures in relaxing astrophysical plasmas.

With the above scenario of magnetohydrodynamic relaxation in astrophysical plasmas, in the thesis, we first numerically explore the physics of spontaneous formation of current sheets and assess the important of magnetic field lines topology in the generation. For the purpose, we employ a novel approach of describing the plasma evolution in terms of magnetic flux surfaces instead of the vector magnetic field. The approach provides a direct visualization of the current sheet formation which is helpful in understanding the governing dynamics. The presented computations confirm spontaneous development of current

sheets through favorable contortions of magnetic flux surfaces where two oppositely directed parts of either the same or different field line(s) come to close proximity while the plasma undergoes a topology-preserving viscous relaxation from an initial non-equilibrium state with interlaced magnetic field lines. Importantly, these current sheet are distributed throughout the computational volume with no preference for favorable sites like magnetic nulls or field reversal layers. However for magnetic field with less interlaced magnetic field lines, the simulations show the development of current sheets only at the favorable sites. These current sheets originate as two sets of anti-parallel complimentary magnetic field lines press onto each other.

Further, we explore the ceaseless regeneration of current sheets. For the purpose, we advect vector magnetic field since the flux surface description is valid till onset of magnetic reconnections. Notably with a fixed grid resolution, the magnetic reconnections described in the thesis are related to under-resolved scales—generated by an unbounded increase of magnetic field gradient. The performed computations are then in the spirit of implicit large eddy simulations which regularize the under-resolved scales through simulated reconnections which are concurrent and collocated with developing current sheets. The spontaneous generation of current sheets is ensured by congruency of the computations with the magnetostatic theorem. An important finding of the thesis is the establishment of the comparative scaling of peak current density with spatial resolution for current sheets developing near and away from different magnetic nulls. The results document the current sheets near two dimensional magnetic nulls to have larger strength while exhibiting a stronger scaling than the current sheets close to three dimensional magnetic nulls or away from any magnetic null. The comparative scaling points to a scenario where the energetics of the secondary reconnections is determined by the magnetic topology near a developing current sheet.

Finally, we explore magnetohydrodynamic relaxation with magnetic field line geometry similar to the solar corona. In particular, through numerical simulations we identify the relaxation as an autonomous mechanism for creating a magnetic flux-rope from initial bipolar magnetic field lines and, subsequently,

for triggering and maintaining its ascend via reconnections that occur below the rope. The revealed morphology of the evolution process including onset and ascend of the rope, reconnection locations and the associated topology of the magnetic field lines agrees with observations, and thus substantiates physical realizability of the advocated mechanism. The computations support the scenario where repeated reconnections can generate observed magnetic structures in any high R_M plasma.

Keywords : Magnetohydrodynamics, MHD relaxation, Current sheets, Magnetic reconnections, EULAG

LIST OF PUBLICATIONS

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Publications attached with the thesis

1. *On the role of topological complexity in spontaneous development of current sheets*, **Sanjay Kumar**, R. Bhattacharyya, and P. K. Smolarkiewicz, Physics of Plasmas, **22**, 082903 (2015).

2. *Continuous development of current sheets near and away from magnetic nulls*, **Sanjay Kumar** and R. Bhattacharyya, Physics of Plasmas, **23**, 044501 (2016).