Origin and dynamics of the Primordial Magnetic field in a parity violating plasma

A thesis submitted in partial fulfilment of
the requirements for the degree of

Doctor of Philosophy

by

Arun Kumar Pandey

(Roll No. 11330014)

Under the guidance of

Prof. Jitesh R. Bhatt

Theoretical Physics Division

Physical Research Laboratory, Ahmedabad, India.

DISCIPLINE OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY GANDHINAGAR, GUJARAT, INDIA

2017

To

My Mummy Papa

♡

Declaration

I declare here that this thesis report represents my own ideas in my own words and I have included others ideas with appropriate citations from original sources. I also declare that I have followed all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/fact/source/data in my submission. I understand that any violation of the above can cause disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Arun Kumar Pandey

(Roll No: 11330014)

Date: December 5, 2017

CERTIFICATE

It is certified that the work contained in the thesis titled **"Origin and dynamics of the Primordial Magnetic field in a parity violating plasma"** by **Mr. Arun Kumar Pandey** (Roll No. 11330014), has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

Prof. Jitesh R. Bhatt
(Thesis Supervisor)
Professor,
Theoretical Physics Division
Physical Research Laboratory,
Ahmedabad, India.

Date:

Acknowledgements

It has been a great prerogative to stay in Physical Research Laboratory for several years, where I got a research as well as homely atmosphere throughout my PhD tenure. It gives me a great pleasure to acknowledge all those who supported me directly or indirectly and made this thesis possible.

First and foremost, I wish to express my sincere gratitude to my supervisor, Prof. Jitesh R. Bhatt, for giving me guidance, encouragement and support throughout my PhD tenure that lead up to this thesis. I am very thankful to him for keeping faith in me and giving me encouragement time to time, which was invaluable source of confidence. I am also grateful to him for introducing me to the interesting and challenging problems of the field, which will play an important role in my future research. Special thanks to my collaborator Sampurn Anand for his invaluable support and for careful reading of my thesis.

I am also thankful to Dr. Ramitendranath Bhattacharyya, Dr. Sanjay Saini, Alok Tiwari and Rahul for providing me a very open and friendly atmosphere whenever I visited Udaipur Solar Observatory (USO) for learning the EULAG code. I would also like to thank Prof. Nandita Srivastava for her wonderful wisdom and insight during my second coursework project on the topic of "CME arrival and predictions on Earth and Mars". I take the opportunity to thank Prof. R. Rangarajan, Dr. Namit Mahajan, Prof. Dilip Angom, Prof. Subhendra Mohanty, Prof. S. Goswami, Dr. B.K.Sahoo and Dr. Partha Konar for teaching several useful courses at various times during my Ph.D. I also thank the other faculty members of theory group: Prof. Rindani, Prof. Hiranmaya Mishra, and Dr. Navinder Singh for creating a friendly, interactive atmosphere to work. I am especially thankful to Dr. Namit Mahajan and Prof. R. Rangarajan for useful discussions from which I learned a lot.

I would like to thank my seniors Gulab Bhai, Avdheshji, Naveen Negiji, Yashpal, Dilip Nandi, Girish C., Upendra, Whagesh, Gaurav Tomar, Manojit, Arkoy, Tanmoy C., Bhavya, Anjali, Priyanka, Lata Thakur, Abhishek Attreya, and Shweta Di for their presence at several times. I would also like to give a sincere thank to my batch mate friends Abhaya, Alok, Anirban, Chitra, Gaurava, Girish, Guru, Ikhsu, Kuldeep, Manu, Sanjay, Shraddha and Tanmoy for making a cheerful environment during my Ph.D stay in PRL. Without them my life here in Ahmedabad would have been a hell. They were present at each and every moment of my life. I would also like to thank my Juniors with whom, I interacted most, Rahul Yadav, Bivin, Diptiranjan, Lalit, Pankaj, Newton, Chandan Hati, Rukmani Bai, Kuldeep Pandey, Navpreet, Rupa, Prahlad, Jabir, Ali, Chandan Gupta, Soumik, Aman,

Vishnudath, Arvind Mishraji, Nidhi, Shefali, Rahul K., Varun, Subir, Kaustav, Akanksha, Archita, Balbeer, Ashish, Richa, Ayan, Bhavesh, Bharti and Naveen. Especially, I would like to thank Nidhi, Ayan and Shefali for their mental support and presence during the stressful days of thesis writing. Their fun, loving and friendly environment made my days easy while I was staying in PRL thaltez hostel.

I am also grateful to Bhagyashree and Sujata ben for their sincere support and help whenever I asked. Last, but not the least, I would be nowhere around here without the love and support of my family. Finally, I must also acknowledge the love, support and blessings of friends, teachers, relatives and all known and unknown persons whom I met with or interacted with in life.

Arun Kumar Pandey

Abstract

The Universe is magnetized on all scales that we have observed so far: stars, galaxies, cluster of galaxies etc. Recent observations indicates that typical magnetic field strength in a galaxy or a galaxy-cluster can have is about a few μG and its coherent length is around ten kpc. Recent observations suggest that the intergalactic medium (IGM) have magnetic field in the range of $(10^{-16} - 10^{-9})$ G with the coherent length scales around Mpc. Though it might be possible to explain the observed magnetic field of the galaxies and stars by some kind of astrophysical process, it is hard to explain the observed magnetic field of an IGM void. There exists an intriguing possibility of relating the origin of these large scale magnetic fields with some high-energy process in the early Universe. Thus it is of great interests to study the origin, dynamics and constraints on the magnetic field generated by such mechanism. This forms the prime focus of this thesis which considers the above problem in the context of a high-energy parity violating plasma.

In recent times there has been considerable interest in studying the magnetic field evolution in high-energy parity violating plasma. It is argued that there can be more right-handed particles over left-handed particles due to some process in the early Universe at temperatures T very much higher than the electroweak phase transition (EWPT) scale (T ~100GeV). Their number is effectively conserved at the energy scales much above the electroweak phase transitions and this allows one to introduce the chiral chemical potentials $\mu_R(\mu_L)$. However , at temperature lower than $T \sim 80$ TeV processes related with the electron chirality flipping may dominate over the Hubble expansion rate and the chiral chemical potentials can not be defined. Further the right handed current is not conserved due to the Abelian anomaly in the standard model (SM) and it is the number density of the right handed particles are related with the helicity of the fields as $\partial_\tau(\Delta\mu + \frac{\alpha_2}{\pi}\mathcal{H}_B) = 0$. (Here $\Delta\mu$, α_2 and $\mathcal{H}_B$ represents the chiral chemical imbalance, fine structure constant and magnetic helicity respectively). Therefore even if initially when there is no magnetic field, a magnetic field can be generated at the cost of the asymmetry in the number density of the left and right handed

particles in the plasma. Recently, it has been interesting development in incorporating the parity -violating effects into a kinetic theory formalism by including the effect of the Berry curvature. Berry curvature term takes into account chirality of the particles. By using this modified kinetic equation, we show that chiral-imbalance leads to generation of hypercharge magnetic field in the plasma in both the collision dominated and collisionless regimes. We show that in the collision dominated regime, chiral vortical effects can generate a chiral vorticity and magnetic field. Typical strength of the magnetic field in the collision and collisionless regime are 10^{27} G at $10^5/T$ length scale and a magnetic field of strength 10^{31} G at $10/T$ length scale at a temperature $T \sim 80$ TeV. We also show that the estimated values are consistent with the present observations.

We also show that in the presence of chiral imbalance and gravitational anomaly, a magnetic field of the strength 10^{30} G can be generated at a scale of 10^{-18} cm (much smaller than the Hubble length scale i.e. 10^{-8} cm). The idea is that in the presence of the gravitational anomaly, the current expression for the chiral plasma consists of a vortical current, proportional to square of temperature i.e. T^2. The silent feature of this seed magnetic field is that it can be generated even in absence of chiral charge. In this work we have considered the scaling symmetry of the chiral plasma to obtain the velocity spectrum. Under this scaling symmetry in presence of gravitational anomaly, amount of energy at any given length scale is much larger than the case where only chiral asymmetry is considered. We also show that under such scenario energy is transferred from large to small length scale, which is commonly known as inverse cascade.

In the context of chiral plasma at high energies, there exist new kind of collective modes [*e.g.*, the chiral Alfv́en waves] in the MHD limit and these modes exist in addition to the usual modes in the standard parity even plasma. Moreover, it has been shown that chiral plasmas exhibit a new type of density waves in presence of either of an external magnetic field or vorticity and they are respectively known as Chiral Magnetic Wave (CMW) and the Chiral Vortical Wave (CVW). In this regard we have investigated the collective modes in a magnetized chiral plasma and the damping mechanisms of these modes using first order and second

hydrodynamics. Using first order conformal hydro, we obtained previously derived modes in the chiral plasma. However we show in addition that these modes get split into two modes in presence of the first order viscous term. By using second order conformal magnetohydrodynamics, we show that there are a series of terms in the dispersion relation and these terms are in accordance with the results obtained using AdS/CFT correspondence. We also calculated one of the transport coefficients related with the second order magnetohydrodynamics.

Keywords: Cosmology, Primordial Magnetic Field, EW phase transition, Left Right symmetric model, Turbulence theory, Kinetic theory, CMB, BBN

Contents

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List of terms used in the thesis

Short name/ Symbol	Definition / meaning
IGM	Inter Galactic Medium
ICM	Inter Cluster Medium
EGMF	enter galactic magnetic field
MHD	Magnetohydrodynamics
CMB	Cosmic Microwave Background
BBM	Biermann Battery Mechanism
BBN	Big Bang Baryogenesis
CME	Chiral Magnetic Effect
ChMHD	Chiral Magnetohydrodynamics
CVE	Chiral Vortical Effect
CVW	Chiral Vortical Waves
CAW	Chiral Álfven Waves
CMW	Chiral Magnetic Waves
CSE	Chiral separation effect
EM	Electromagnetic
SM	Standard Model
EW	Electroweak
GUT	Grand Unified Theory
QCD	Quantum Chromodynamics
BAU	Baryon Asymmetry of the Universe

Short name/ Symbol	Definition / meaning
n D	n dimensional space
kpc/Mpc	kiloparsec/megaparsec
eV	electron volt
keV	kilo electron volt
MeV	mega electron volt
GeV	giga electron bolt
H	Hubble constant
ρ	Matter energy density
ρ_γ	Radiation energy density
$\boldsymbol{\omega}$	vorticity vector
m_p	mass of the ions
k_B	Boltzmann's coefficient
c	speed of light
σ	electrical conductivity
α	fine structure constant
m_e	electron mass
μ	micro
$\hbar$	reduced Planck constant ($\hbar = h/2\pi$)
M_{pl}	Planck Mass
G	Gauss
$\Re$	set of Real number

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List of Publications

1. **Arun Kumar Pandey**, Jitesh R. Bhatt, *Primordial magnetic field and kinetic theory with Berry curvature*, Phys. Rev. D, 94, 043536, doi: 10.1103/PhysRevD.94.043536.

2. **Arun Kumar Pandey**, Jitesh R. Bhatt, *Primordial Generation of Magnetic Fields*, XXI DAE-BRNS High Energy Physics Symposium: Proceedings, Guwahati, India, December 8-12, 2014, Springer Proceedings in Physics, doi: 10.1007/978-3-319-25619-1_62.

3. **Arun Kumar Pandey**, Jitesh R. Bhatt, Sampurnand *'Chiral Battery, scaling laws and magnetic fields*, JCAP **1707**, no. 07, 051 (2017) doi:10.1088/1475-7516/2017/07/051

Publications attached with the thesis

1. **Arun Kumar Pandey**, Jitesh R. Bhatt, *Primordial magnetic field and kinetic theory with Berry curvature*, Phys. Rev. D, 94, 043536, doi: 10.1103/PhysRevD.94.043536.

2. **Arun Kumar Pandey**, Jitesh R. Bhatt, *Primordial Generation of Magnetic Fields*, XXI DAE-BRNS High Energy Physics Symposium: Proceedings, Guwahati, India, December 8-12, 2014, Springer Proceedings in Physics, doi: 10.1007/978-3-319-25619-1_62.

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