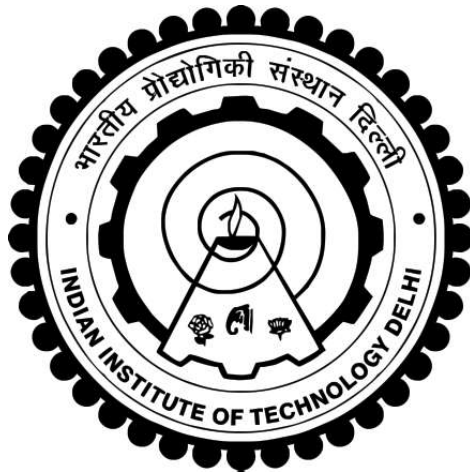


**LOWER HYBRID TURBULENCE AND
PARTICLE ACCELERATION DUE TO
RECONNECTING CURRENT SHEETS IN
MAGNETOPAUSE RECONNECTION
REGIONS**

MANOJ KUMAR UPADHYAY



***DEPARTMENT OF ENERGY SCIENCE AND
ENGINEERING***

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

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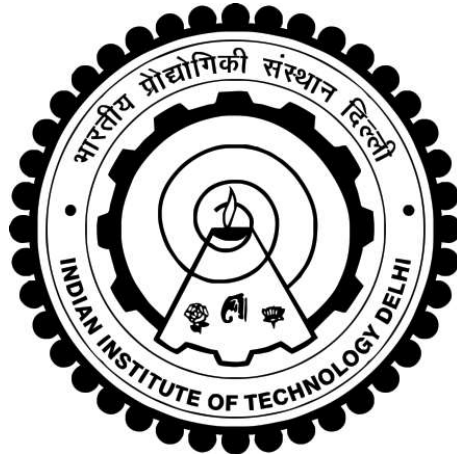
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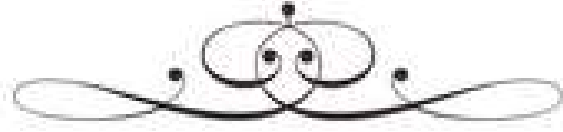
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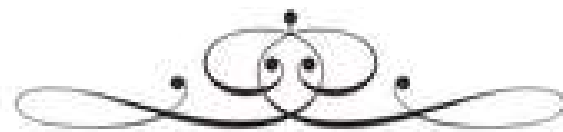
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JULY 2025



Dedicated to
my
“Beloved Parents
and
Sister”

*Who have always been my source of inspiration, guidance and encouragement, and my
gratitude for whom can never be put into words.*



CERTIFICATE

This is to certify that the thesis entitled “*Lower Hybrid Turbulence and Particle Acceleration Due to Reconnecting Current Sheets in Magnetopause Reconnection Regions*” being submitted by **Manoj Kumar Upadhyay** to the Indian Institute of Technology, Delhi is worthy of consideration for the award of the degree of ‘*Doctor of Philosophy*’ in Department of Energy Science and Engineering and is a record of bona fide research work carried out by him.

The thesis has reached the standards fulfilling the requirement of the regulations relating to the degree. The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma. I approve the thesis for the award of the aforesaid degree.

Date:

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(MANOJ KUMAR UPADHYAY)

Abstract

The intricate and intellectually challenging process of wave-wave coupling, a phenomenon that can push the system into a turbulent state, is a key focus of this thesis. The Magnetopause reconnection region, a complex and dynamic environment, has identified many wave modes. This thesis, a testament to the in-depth research and understanding, is built upon the investigation of wave-wave coupling using numerical modelling and computer simulations.

The MMS mission's observations of Lower Hybrid Waves (LHWs) and turbulence in the Magnetopause reconnection region of Earth's atmosphere are of paramount importance. These observations not only shed light on the behaviour of LHWs in reconnection regions but also provide crucial insights into their role in anomalous resistivity, particle heating, energy transfer, and particle diffusion. The mission's findings, including the observation of turbulence, temperature anisotropy, and anomalous heating near reconnection regions in Magnetopause, form the cornerstone of this thesis. The thesis is dedicated to a comprehensive study of LHWs in reconnection regions of Magnetopause, leveraging the invaluable insights provided by the MMS mission.

This thesis aims to investigate the evolution of LHW, the effect of nonlinearity and field perturbations (magnetic islands) on LHW dynamics, and the evolution of current sheets near reconnection regions of Magnetopause. Further, the precise mechanism of particle heating and anisotropy observed in the Magnetopause is unknown. LHW can be a source of electron acceleration and electron temperature anisotropy in Magnetopause reconnection regions. This work has tried to explain these phenomena using a 3D LHW model, a computational model that simulates the behaviour of LHW in a three-dimensional space. It then discusses the similarities of the simulation results with MMS observations.

The first chapter of the thesis serves as a concise introduction to the plasma fundamentals, discussing various wave modes, turbulence, and magnetic reconnection in the Earth's Magnetopause. It also outlines the motivation and scientific goals of the thesis. The second chapter presents a 'simple 2D model' to explain lower hybrid turbulence in the Magnetopause. Based on the concept of nonlinear wave-wave coupling, this model provides a practical application of concepts, considering the interaction between pump LHW and low-frequency magnetosonic wave (MSW).

The third chapter shows the effect of nonlinearity and the magnetic islands on lower hybrid turbulence and current sheets. The results show that both nonlinear effects and magnetic islands are responsible for the evolution of LHWs and current sheets to a chaotic and turbulent state. This chapter concludes that to study the LHW evolution, one will have to consider the reconnection process, along with nonlinearity. The fourth chapter discusses a model of 3D electrostatic lower hybrid wave (LHW) in cold magnetized plasma with magnetic islands. The simulation results illustrate the formation and evolution of localised structures and the current sheets. The turbulent power spectra have also been studied. The distribution function of energetic electrons due to these turbulent structures is obtained using the Fokker-Planck diffusion Equation with the new velocity space diffusion coefficient.

The fifth chapter studies lower hybrid waves (electromagnetic mode) and turbulence in Magnetopause's presence of magnetic islands (at the reconnection sites). Simulations show the turbulent power spectra with scaling of $k^{-2.8}$ (approximately) and $k^{-2.1}$ (approximately) along perpendicular and parallel directions, respectively, indicating anisotropy. The power-law scaling of turbulence generation has been used to study the formation of the thermal tail of energetic electrons. The fractional diffusion method has also been exploited to determine electron acceleration, plasma heating and temperature anisotropy. LHW may be responsible for the acceleration of the energetic electrons and temperature anisotropy in Magnetopause.

The Sixth chapter further improves the model by including the thermal effects. The lower hybrid waves (LHWs) should be locally excited by the electron beam (produced by the magnetic reconnection process) at the reconnection sites. The model is solved numerically with the pseudo-spectral method for spatial integration, and the finite difference method with a modified predictor-corrector approach for time domain integration. The spatiotemporal evolution of current sheets and the interplay between current sheets and LHW for beam-driven mode is also discussed. From simulations, one can anticipate that the LHW interacts with current sheets and fragments them into small-scale structures. From the semi-analytic approach, the current sheet dimensions may depend upon the wave mode, thermal effects, temperature profile, and anisotropy.

The thesis concludes with a summary of the findings and a thought-provoking proposal for future work. These proposed studies, if undertaken, have the potential to not only further enrich the understanding of lower hybrid waves and turbulence in Magnetopause reconnection regions but also to open up new and exciting avenues for research in the field.

सार

तरंग-तरंग युग्मन की जटिल और बौद्धिक रूप से चुनौतीपूर्ण प्रक्रिया, एक ऐसी घटना जो सिस्टम को अशांत अवस्था में धकेल सकती है, इस थीसिस का मुख्य फोकस है। मैग्नेटोपॉज़ पुनर्संयोजन क्षेत्र, एक जटिल और गतिशील वातावरण, ने कई तरंग मोड की पहचान की है। यह थीसिस, गहन शोध और समझ का प्रमाण है, संख्यात्मक मॉडलिंग और कंप्यूटर सिमुलेशन का उपयोग करके तरंग-तरंग युग्मन की जांच पर आधारित है।

पृथ्वी के वायुमंडल के मैग्नेटोपॉज़ रीकनेक्शन क्षेत्र में लोअर हाइब्रिड वेक्स (LHWs) और अशांति के MMS मिशन के अवलोकन अत्यंत महत्वपूर्ण हैं। ये अवलोकन न केवल रीकनेक्शन क्षेत्रों में LHWs के व्यवहार पर प्रकाश डालते हैं, बल्कि असामान्य प्रतिरोधकता, कण तापन, ऊर्जा हस्तांतरण और कण प्रसार में उनकी भूमिका के बारे में महत्वपूर्ण जानकारी भी प्रदान करते हैं। मैग्नेटोपॉज़ में रीकनेक्शन क्षेत्रों के पास अशांति, तापमान विषमता और असामान्य तापन के अवलोकन सहित मिशन के निष्कर्ष इस थीसिस की आधारशिला हैं। यह थीसिस मैग्नेटोपॉज़ के रीकनेक्शन क्षेत्रों में LHWs के व्यापक अध्ययन के लिए समर्पित है, जो MMS मिशन द्वारा प्रदान की गई अमूल्य अंतर्दृष्टि का लाभ उठाता है।

इस शोध का उद्देश्य LHW के विकास, LHW गतिशीलता पर गैर-रैखिकता और क्षेत्र गड़बड़ी (चुंबकीय द्वीप) के प्रभाव और मैग्नेटोपॉज़ के पुनर्संयोजन क्षेत्रों के पास धारा शीट के विकास की जांच करना है। इसके अलावा, मैग्नेटोपॉज़ में देखे गए कण हीटिंग और अनिसोट्रोपी का सटीक तंत्र अज्ञात है। LHW मैग्नेटोपॉज़ पुनर्संयोजन क्षेत्रों में इलेक्ट्रॉन त्वरण और इलेक्ट्रॉन तापमान अनिसोट्रोपी का स्रोत हो सकता है। इस कार्य ने 3D LHW मॉडल, एक कम्प्यूटेशनल मॉडल का उपयोग करके इन घटनाओं को समझाने की कोशिश की है जो तीन-आयामी अंतरिक्ष में LHW के व्यवहार का अनुकरण करता है। फिर यह MMS अवलोकनों के साथ सिमुलेशन परिणामों की समानताओं पर चर्चा करता है।

थीसिस का पहला अध्याय प्लाज्मा की बुनियादी बातों का संक्षिप्त परिचय है, जिसमें पृथ्वी के मैग्नेटोपॉज़ में विभिन्न तरंग मोड, अशांति और चुंबकीय पुनर्संयोजन पर चर्चा की गई है। यह थीसिस की प्रेरणा और वैज्ञानिक लक्ष्यों को भी रेखांकित करता है। दूसरा अध्याय मैग्नेटोपॉज़ में LHW अशांति को समझाने के लिए एक 'सरल 2D मॉडल' प्रस्तुत करता है। नॉनलाइनियर वेव-वेव कपलिंग की अवधारणा के आधार पर, यह मॉडल पंप LHW और कम आवृत्ति वाले मैग्नेटोसोनिक वेव (MSW) के बीच बातचीत पर विचार करते हुए अवधारणाओं का एक व्यावहारिक अनुप्रयोग प्रदान करता है।

तीसरा अध्याय गैर-रैखिकता और चुंबकीय द्वीपों के निम्न संकर अशांति और धारा शीट पर प्रभाव को दर्शाता है। परिणाम दर्शाते हैं कि गैर-रैखिक प्रभाव और चुंबकीय द्वीप दोनों ही LHW और धारा शीट के अव्यवस्थित और अशांत अवस्था में विकास के लिए जिम्मेदार हैं। यह अध्याय निष्कर्ष निकालता है कि LHW विकास का अध्ययन करने के लिए, गैर-रैखिकता के साथ-साथ पुनर्संयोजन प्रक्रिया पर भी विचार करना होगा। चौथा अध्याय चुंबकीय द्वीपों के साथ ठंडे चुंबकीय प्लाज्मा में 3D इलेक्ट्रोस्टैटिक निम्न संकर तरंग (LHW) के

एक मॉडल पर चर्चा करता है। सिमुलेशन परिणाम स्थानीय संरचनाओं और धारा शीट के गठन और विकास को दर्शाते हैं। अशांत शक्ति स्पेक्ट्रा का भी अध्ययन किया गया है। इन अशांत संरचनाओं के कारण ऊर्जावान इलेक्ट्रॉनों का वितरण कार्य, नए वेग स्थान प्रसार गुणांक के साथ फोल्कर प्लैंक प्रसार समीकरण का उपयोग करके प्राप्त किया जाता है।

पाँचवाँ अध्याय मैग्नेटोपॉज़ की चुंबकीय द्वीपों (पुनः संयोजन स्थलों पर) की उपस्थिति में निम्न संकर तरंगों (विद्युत चुम्बकीय मोड) और अशांति का अध्ययन करता है। सिमुलेशन क्रमशः लंबवत और समानांतर दिशाओं के साथ $k^{-2.8}$ (लगभग) और $k^{-2.1}$ (लगभग) स्केलिंग के साथ अशांत शक्ति स्पेक्ट्रा दिखाते हैं, जो अनिसोट्रॉपी को दर्शाता है। ऊर्जावान इलेक्ट्रॉनों की थर्मल पूंछ के गठन का अध्ययन करने के लिए अशांति उत्पादन की शक्ति-कानून स्केलिंग का उपयोग किया गया है। इलेक्ट्रॉन त्वरण, प्लाज्मा हीटिंग और तापमान अनिसोट्रॉपी को निर्धारित करने के लिए आंशिक प्रसार विधि का भी उपयोग किया गया है। मैग्नेटोपॉज़ में ऊर्जावान इलेक्ट्रॉनों के त्वरण और तापमान अनिसोट्रॉपी के लिए LHW जिम्मेदार हो सकता है।

छठा अध्याय थर्मल प्रभावों को शामिल करके मॉडल को और बेहतर बनाता है। निम्न हाइब्रिड तरंगों (LHW) को पुनर्संयोजन स्थलों पर इलेक्ट्रॉन बीम (चुंबकीय पुनर्संयोजन प्रक्रिया द्वारा उत्पादित) द्वारा स्थानीय रूप से उत्तेजित किया जाना चाहिए। मॉडल को स्थानिक एकीकरण के लिए छद्म-स्पेक्ट्रल विधि और समय डोमेन एकीकरण के लिए संशोधित भविष्यवक्ता-सुधारक दृष्टिकोण के साथ परिमित अंतर विधि के साथ संख्यात्मक रूप से हल किया जाता है। बीम-संचालित मोड के लिए करंट शीट के स्थानिक-समय विकास और करंट शीट और LHW के बीच परस्पर क्रिया पर भी चर्चा की गई है। सिमुलेशन से, कोई यह अनुमान लगा सकता है कि LHW करंट शीट के साथ अंतःक्रिया करता है और उन्हें छोटे पैमाने की संरचनाओं में विभाजित करता है। अर्ध-विश्लेषणात्मक दृष्टिकोण से, करंट शीट के आयाम तरंग मोड, थर्मल प्रभाव, तापमान प्रोफ़ाइल और अनिसोट्रॉपी पर निर्भर हो सकते हैं।

थीसिस निष्कर्षों के सारांश और भविष्य के काम के लिए एक विचारोत्तेजक प्रस्ताव के साथ समाप्त होती है। यदि ये प्रस्तावित अध्ययन किए जाते हैं, तो न केवल मैग्नेटोपॉज़ रीकनेक्शन क्षेत्रों में कम हाइब्रिड तरंगों और अशांति की समझ को और समृद्ध करने की क्षमता है, बल्कि इस क्षेत्र में अनुसंधान के लिए नए और रोमांचक रास्ते भी खुलेंगे।

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