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論 文 内 容 要 旨

（NO.　1）

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学位論文の 題　　　目	Characteristics of IPDP-type EMIC waves and their relation to relativistic electron precipitation based on ground-based and satellite observations （地上ー衛星観測に基づくIPDPタイプEMIC波動の特徴と相対論的電子降下との関連性に関する研究）		

Electromagnetic ion cyclotron (EMIC) waves are left-hand polarized waves in Pc1-2 frequency range. They are excited near the magnetic equator by anisotropic ring current ions. EMIC waves are one of the interesting plasma waves in the magnetosphere in that they interact with both ring current protons and relativistic electrons. Clarifying of the behavior of EMIC waves contributes to a comprehensive understanding of the variability of the inner magnetosphere, especially the ring current and the outer radiation belt. Electron scattering by EMIC waves has been considered as one of the mechanisms to cause the loss of the outer radiation belt. Evaluation of the contribution of EMIC waves to the electron loss is the important issue in understanding and prediction of the outer radiation belt variations.

There are two unresolved issues about excitation of EMIC waves and electron scattering by EMIC waves. One is the mechanism of frequency increase of intervals of pulsations of diminishing periods (IPDP). IPDP is a type of EMIC waves characterized by an increase in frequency during the event and occur in the evening sector of the magnetosphere. Some studies suggested that IPDP-type EMIC waves are more likely to be associated with relativistic electron precipitation (REP) than other EMIC waves. However, there is no definitive answer about the mechanism of frequency increase and the reason why IPDPs are associated with REP. Another is conditions favorable for pitch angle scattering of relativistic electrons by EMIC waves. Many previous studies have revealed that EMIC waves can occur in various L-values and magnetic local time (MLT) in the magnetosphere. However, few studies have statistically investigated the characteristics of EMIC waves causing REP.

Purposes of this thesis are (1) to reveal the mechanism of frequency increase of IPDP-type EMIC waves and (2) to understand favorable conditions for pitch angle scattering of relativistic electrons by EMIC waves. By achieving the purpose of (1) and (2), we aim to comprehensively understand how generation of EMIC waves and the associated REP are related to the dynamics of the inner magnetosphere.

We analyzed IPDP-type EMIC waves that occurred on 19 April 2017 from the ground and the satellite observations. Observations by POES and the ground-based magnetometers indicated that increase in frequency of IPDP was caused by the inward shift of the EMIC wave source region. The source region of EMIC waves moved inward along the midlatitude trough that was used as a proxy of the plasmapause location. This suggests the inward shift of the source region due to the enhancement of the convection electric field. From statistical analysis, we found that upper frequencies of IPDP show a positive correlation with maximum polar cap potential. These results presented that increases in frequency of IPDP on the evening side are explained by the inward shift of the overlap region between the cold plasma and the ring current, which is the favorable region of EMIC wave excitation. It was also found that the built-up plasmasphere and the enhancement of convection electric field or that of the substorm-induced electric field are important for the occurrence of IPDP.

We performed a statistical study of EMIC waves and REP caused by EMIC waves for two years from 1 November 2016 to 31 October 2018. EMIC waves were observed by the ground-based magnetometer installed at Athabasca, Canada. REP events were identified from the VLF radio waves propagating from transmitters at NDK and NLK to the receiver installed at Athabasca. The MLT dependence of all EMIC waves shows higher occurrence rates in the dawn sector. On the other hand, EMIC waves accompanied by REP are localized in the dusk sector and occur during substorms. We found that EMIC waves accompanied by REP are associated with the main phase of geomagnetic storms and that more than half of them seems to occur inside the plasmapause. These results suggest that EMIC waves that occur in the overlap region between the ring current and the dense cold plasma during the storm main phase or substorms are likely to cause REP. It is consistent with previous studies that describe that electron resonant energy with EMIC waves lowers in high plasma density regions.

It is proposed that the frequency increase of IPDP-type EMIC waves is caused by enhancement of induced/convection electric field associated with substorm and subsequent inward shift of the ring current region toward the Earth. The development of the partial ring current is a necessary precondition for the occurrence of IPDP. This situation primary occurs during the main phase of geomagnetic storms. In the main phase, the overlap region of the ring current and the plasmasphere or plasmaspheric plume is formed and is favorable for both excitation of EMIC waves and pitch angle scattering of relativistic electrons by EMIC waves in the dusk sector. In addition to these favorable conditions for EMIC wave-driven REP, we propose that the source region of IPDP moves in the radial direction, causing more favorable conditions. The inward drift of the source region allows EMIC waves to be distributed over a wide range of L shells in the entire event. This can make it easier for EMIC waves to encounter high electron flux regions in the outer radiation belt. As a result, EMIC waves can scatter relativistic electrons over a wide range of L shells, leading to electron precipitation into the atmosphere. This mechanism suggests that IPDP-type EMIC waves are more likely to scatter relativistic electrons than EMIC waves generated in other conditions and thus contribute to the loss of the outer radiation belt electrons. We also showed that the decrease in phase space density of relativistic electrons in the outer radiation belt is consistent with the source region extent and the resonant energy of EMIC waves, implying the possible contribution of EMIC waves to the loss of the outer radiation belt in the main phase of geomagnetic storms.

In this thesis, we made use of multiple instruments both on the ground and from the satellite. Combination of both provided the spatial distribution and temporal variation of EMIC waves. Continuous and fixed-point observations on the ground enabled us to investigate the correspondence between EMIC waves and REP.

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論文審査の結果の要旨

電磁イオンサイクロトロン（EMIC）波動は 0.1-5Hz 帯の電磁波で，温度異方性を持つ環電流プロトンによって励起する．EMIC 波動による電子のピッチ角散乱は，放射線帯の電子が大気へ消失する原因の一つと考えられている．この波動の振る舞いの理解は，環電流と放射線帯の包括的な理解に寄与する．

本論文は，EMIC 波動の励起と電子散乱に関する 2 つの未解決問題に取り組んだ．1 つ目は，intervals of pulsations of diminishing periods (IPDP)の発生過程である．IPDP は周波数上昇を示す EMIC 波動の一種で，電子散乱との関連性が報告されているが，周波数上昇過程と電子散乱過程の繋がりは未解明であった．2 つ目は，EMIC 波動が電子を散乱する条件である．電子散乱を引き起こす波動の特徴を統計的に調べた研究は少なく，理論予測の検証が不足していた．本論文は，(1)IPDP の周波数上昇過程と電子散乱に対する IPDP の役割と，(2)EMIC 波動による電子散乱の条件の解明を目的とした．

(1)2017 年 4 月 19 日に発生した IPDP に対して，衛星と地上の統合データ解析から EMIC 波動の発生領域とその時間変化を同定し，IPDP の周波数上昇の原因が波動発生領域の動径方向の移動であることを明らかにした．波動の発生領域は中緯度トラフと伴に移動しており，104 例の IPDP の統計解析から，周波数上昇と極冠電位の間に正の相関が示された．これらの結果から，波動発生領域の移動の原因は、対流電場の増大であることが明らかにされた．波動発生領域の移動範囲と電子の共鳴エネルギーは，放射線帯電子の消失が観測された領域・エネルギーと対応していた．IPDP は動径方向の移動により幅広い領域で電子を散乱し，放射線帯の消失に影響することを指摘した．

(2)独自の地上観測データを用い、波動の散乱で生じた電子降下現象の統計解析が行われた．電子降下を伴う EMIC 波動の発生領域は，夕方側に局在しサブストーム中に発生すること，磁気嵐主相時にプラズマ圏内で発生しやすいことが初めて明らかにされた．磁気嵐の主相には，発達した環電流とプラズマ圏の重複領域が夕方側に生じ，この領域が波動の励起と電子散乱の両方に好都合であるとする理論的予測を支持する．

IPDP の基本性質が動径方向の移動であること、その性質により放射線帯電子が広範囲で消失しうることを示したことは，この論文が導いた重要な知見であり，平井あすかさんが研究活動を行うに必要な高度の研究能力と学識を有することを示している．提出された博士論文は，博士（理学）の学位論文として合格と認める．