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## 論 文 目 次

### Contents

Acknowledgements	i
Abstract	iii
1 General introduction	1
1.1 Jovian auroras and radio emissions	1
1.2 Introduction to Io-related auroras	3
1.2.1 Current-voltage relationship of trailing tail aurora	3
1.2.2 Footprint brightness of the main auroral spot	5
1.3 The role of the electron convection term	6
1.3.1 Generation of the parallel electric field	6
1.3.2 Modification of the ion acoustic mode	7
1.3.3 Theory of the double layer formation in the fluid frame	9
1.4 Introduction to the Io-related decametric radiation	10
1.4.1 Morphological features	10
1.4.2 Longitudinal distribution of Io-DAM occurrence	11
1.4.3 Relationship of the surface magnetic intensity with ionospheric conductance	12
1.5 Purpose of this thesis	14

1.5.1 Purpose of 1D simulations	14
1.5.2 Purpose of 2D simulations	14
2 Study of the current-voltage relationship in the Io tail aurora	25
2.1 1D simulation model	25
2.1.1 Extended multi-magnetofluid equations	25
2.1.2 Simulation condition	27
2.2 1D simulation results	29
2.2.1 Formation of the HATL	29
2.2.2 Voltage and balanced altitude of the HATL	31
2.2.3 Origin of the current-voltage relationship	33
2.2.4 Meaning of our current-voltage relationship	35
2.3 Discussion	36
2.3.1 Source region of the Io-DAM fringe	36
2.3.2 Potential gap indicated by the change of the S-burst drift rate	38
2.3.3 Velocity distribution indicated by the vertical brightness profile	39
2.3.4 Limitations of simulation parameters	40
2.4 Short summary	42
3 Study of the longitudinal distribution of Io-DAM occurrence probability	51
3.1 2D simulation model	51
3.1.1 Hall MHD equations	51
3.1.2 Simulation region	52
3.1.3 Implementation of the Jovian ionosphere	53
3.1.4 Implementation of Io	54
3.1.5 Other noteworthy conditions	56
3.2 2D simulation results	57
3.2.1 Interpretation of global dynamics	57
3.2.2 Symmetrical ionospheric conductance	58
3.2.3 Asymmetrical ionospheric conductance	61
3.2.4 Io at the northern edge of the torus	61
3.3 Discussion	63
3.3.1 Reason of suppressed/enhanced Io-DAM occurrence	63
3.3.2 Emission periodicity of Io-DAM	64
3.3.3 Longitudinal length of the main auroral spot	65
3.3.4 Relative brightness of the second auroral spot	66
3.3.5 Limitations of our 2D simulation method	67
3.3.6 Lead angle of Io-DAM fringe	68
3.4 Short summary	69
4 Summary and conclusions	81
A Numerical Scheme	85
A.1 Advection	85

A.2 Divergence B correction .....	88
References .....	89

## 論 文 内 容 要 旨

Satellite Io interacts with the plasma torus surrounding Io's orbit and it leads to electron accelerations by parallel electric fields. The accelerated electrons precipitate into the Jovian atmosphere and excite Io-related auroras. Io-related aurora is composed of multiple spots and trailing tail. The spot auroras appear at the initial arrival point of Alfvén wave radiated from Io (main spot), the arrival points of reflected Alfvén wave (reflected Alfvén wing spots, or RAW spots), and the magnetic conjugate points of these arrival points. The tail aurora extends for approximately  $100^\circ$  of longitude along the footpath of the Io's orbit. Observations [Gérard *et al.*, 2002; Bonfond *et al.*, 2009] indicate that the field-aligned voltage is constant while the parallel current density decreases in the downstream direction. The mechanism that realizes the current-voltage relationship of the Io tail aurora remains unresolved. The main auroral spot is brighter when Io is closer to the centrifugal equator [Serio and Clarke, 2008; Wannawichian *et al.*, 2010]. This would be because of the intensity of the Io-torus interaction modulated by Io's magnetic latitude. On the other hand, the brightness of the first RAW spot is comparable to the main spot only for the hemisphere to which Io is close [Bonfond *et al.*, 2008]. The mechanism that realizes this trend is unresolved. In this thesis, we address the mechanism that realizes the current-voltage relationship of the Io tail aurora, and the brightness of the multiple spots.

Part of the kinetic energy of the Io-related auroral electrons is converted to the Io-related decametric radio emission called Io-DAM. There are two types of Io-DAM named arc and fringe. The arc is a curved envelope of narrowband bursts, and the fringe is repetitive wideband bursts. Despite the excitation mechanism and the source region of the arc have become clear [Hess *et al.*, 2008, 2010, 2011], those of the fringe remain unresolved. Io-DAM occurrence probability exhibits different longitudinal variation from the main spot brightness [Goertz, 1983; Hess *et al.*, 2011]. In this thesis, we address the source region of Io-DAM fringes and longitudinal distribution of Io-DAM occurrence probability.

We apply a new multi-magnetofluid code to the Io-Jupiter system to clarify the origin of the current-voltage relationship and investigate the source location and excitation mechanism of Io-DAM fringe. The code solves a set of equations that includes the electron convection term in Ohm's law, which enables us to simulate the current-driven ion acoustic instability in the fluid frame.

Hall MHD equations are solved in the corotating meridional plane including the Jovian ionosphere with finite thickness. The ionospheric Pedersen conductance is expected to be anti-proportional to the surface magnetic intensity. We assume asymmetrical conductance between the northern and southern ionosphere for  $110^\circ$  and symmetrical conductance for  $290^\circ$ , based on the VIPAL magnetic field model. The following conclusions are obtained in this study.

### Origin of the current-voltage relationship of Io tail aurora

The current-driven ion acoustic instability leads to a formation of a transition layer at a high altitude, which accelerates the magnetospheric electrons and blocks the magnetospheric ions, leading to the formation of a

density depleted region called an auroral cavity. We find that if the ionospheric proton density decreases at the same rate as the parallel current density, the timescale on which the transition layer disappears is consistent with the longitudinal extent of the tail aurora, and the field-aligned voltage of the transition layer is constant all along the tail.

#### **Source region of Io-DAM fringe**

In the auroral cavity, the shell-driven maser is prior to the loss cone-driven maser, since there is no Maxwellian core of electrons. As for the shell-driven maser, the emission beam angle is almost  $90^\circ$  and independent of the local cyclotron frequency. The frequency-independent beam angle is consistent with the observed wide bandwidth of the fringe. The maximum altitude of high-altitude transition layer is comparable to the low-frequency limit of Io-DAM. These facts would support the idea that the source region of Io-DAM fringe is in the auroral cavity.

#### **Longitudinal distribution of Io-DAM occurrence probability**

Above the northern ionosphere, the parallel current density integrated in the latitudinal direction is estimated to be 1.5-2.0 times larger for the symmetrical conductance than for the asymmetric conductance further than  $20^\circ$  downstream of the main spot. This indicates that, if the Io-DAM lead angle is large, the suppressed Io-DAM occurrence probability radiated from the northern hemisphere around a longitude of  $110^\circ$  would be caused by the north-south asymmetry of the footprint magnetic intensity. On the other hand, a strong current density conducted into the south at  $110^\circ$  may be the source of so-called Io-D emissions radiated from the southern hemisphere around this longitude.

#### **Brightness of the first RAW spot compared to the adjacent main spot**

The amplitude of the parallel current density above the first RAW spot is as large as that above the adjacent main spot only for the northern ionosphere when Io is located at the northern edge of the torus. Our simulation results suggest that the first RAW spot in the northern hemisphere originates from the Alfvén wave corresponding to the main spot of the southern hemisphere, and it is strong because of the superposition of the initially northward radiated Alfvén wave from Io onto the southward radiated Alfvén wave after the reflection at the northern ionosphere.

## 論文審査の結果の要旨

木星の衛星イオは公転軌道を取りまくイオトラスと相互作用し、沿磁力線電場による電子加速を引き起こす。加速された電子は木星大気に降下しイオ関連オーロラを生じる。イオ関連オーロラは複数のスポットオーロラとテイルオーロラから構成されている。スポットオーロラはイオからのアルフベン波が最初に到達する点(メインスポット)、反射したアルフベン波が到達する点(RAWスポット)、およびそれらの磁気共役点に表れる。テイルオーロラはイオ公転軌道に沿って経度およそ100度の幅に広がって出現する。観測によれば、テイルオーロラ上空では、沿磁力線電位差は一定だが、電流密度はテイル下流ほど小さい。この電流-電圧関係のメカニズムは未だ解明されていない。

イオ関連オーロラを生じる加速電子の運動エネルギーの一部は、Io-DAMと呼ばれる木星デカメータ電圧に変換される。Io-DAMの出現頻度は、スポットオーロラの明るさとは異なった経度依存性を示す。Io-DAMにはアーク・フリンジと呼ばれる2種類の放射がある。ダイナミックスペクトル上で、アークはカーブを描く狭帯域放射、フリンジは周期性をもった広帯域放射として観測される。先行研究でアークの放射メカニズム・放射源位置は明らかにされてきたが、フリンジの放射メカニズム・放射源位置は未解明である。

本研究では、まず、新たな多流体シミュレーションコードをイオ-木星系に適用し、テイルオーロラの電流-電圧関係の解明、Io-DAMフリンジの発生メカニズムの検討を行った。シミュレーションコードでは、電子移流項を含むような方程式系を解くことで、流体の枠組内で電流駆動型イオン音波不安定を再現することを可能とした。次に、Io-DAMの出現頻度及びスポットオーロラの明るさの経度分布解明のため、木星と共回転する子午面内において有限の厚さの木星電離圏を考慮して、Hall MHD方程式系を解いた。Pedersen伝導度は、表面の磁場強度に反比例するものと仮定し、VIPAL磁場モデルに従って経度110度では南北非対称な、290度では南北対称な伝導度を設定した。本研究によって以下の結論が得られた：

イオテイルオーロラの電流-電圧関係の起源。電流駆動型イオン音波不安定が高高度遷移層を形成する。この遷移層は磁気圏電子を加速し、磁気圏イオンをブロックし、その結果、オーロラキャビティと呼ばれる密度希薄層が形成される。電離圏プロトンと沿磁力線電流が同じ速さで減少した場合に遷移層が消滅する時間スケールが観測されるテイルオーロラの経度幅に一致していること、遷移層の沿磁力線電位差がテイルに沿って一定であることを見出した。

Io-DAMフリンジの放射源位置。Maxwell分布のコアプラズマが存在しないオーロラキャビティ内では、シェル速度分布で駆動されるメーザ不安定が卓越し、放射源のサイクロトロン周波数によらず、放射角はほぼ90度となる。この放射角特性は観測されるフリンジが広帯域であることと整合し、放射源がオーロラキャビティ内であることを示唆している。

Io-DAM出現頻度の経度分布。北半球の電離圏上空では、伝導度が南北非対称な場合に比べ、南北対称な場合に沿磁力線電流が1.5~2倍大きくなることが確かめられた。このことは、北半球の経度110度付近から放射されるIo-DAMの出現頻度の低減が、イオフットプリントでの磁場の南北非対称によって生じることを示している。一方、南半球では110度付近で南北非対称による大きな電流密度が生じることによってIo-D放射が引き起こされている可能性がある。

以上、本論文は著者が自立して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。したがって、松田和也提出の博士論文は、博士(理学)の学位論文として合格と認める。