Ground-satellite observations of high-frequency EMIC waves beyond the Pc1 range

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Several high frequency geomagnetic pulsations beyond the Pc1 frequency range were observed by mid-latitude ground-based induction magnetometer at Moshiri, Japan. We found that Van Allen Probe B observed magneto sonic wave (MSW) and electro-magnetic ion cyclotron (EMIC) waves during the inbound orbit from L=4 to 2 simultaneously with one of ground high-frequency Pc1 events on September 11, 2015. Appearances of MSW preceded to EMIC waves. This conjugate observations indicate that mid-latitude high-frequency Pc1 pulsations beyond the range result from propagations of EMIC waves existing deeply inside the inner magnetosphere, and the source of EMIC wave is probably MSW. In the presentation, we show the details of analyzed results both ground and satellite data including these wave polarizations. In addition, we show statistical characteristics of occurrence time, duration, magnetic local time, spectral type, and relation to geomagnetic storm of high-frequency Pc1 at mid latitudes in 2015.

Sequence of Pi2 Pulsations and Poloidal Standing Alfven Waves Observed in the Midnight Sector

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Pi2 pulsations are routinely observed in the midnight sector during substorms. These are considered to be large-scale fast mode waves, which propagate to various latitudes on the ground. We report a sequence of Pi2-band oscillations observed by the Van Allen Probes (RBSP) spacecraft in the midnight sector during a moderately active period on 24 March 2013. In the time series plots of the electric and magnetic field data from each RBSP spacecraft, all events appear similar with a classical Pi2-type wave packet structure. However, cross-phase analysis of the wave fields from the two RBSP spacecraft reveals that some wave packets represent poloidal mode standing Alfven waves with a large (˜50) azimuthal wave number (m). Data from ground magnetometers, the ETS-VIII spacecraft, and the QZS1 spacecraft indicate radial localization of the high-m waves. Presence of high-m poloidal waves in the midnight sector during substorms means that we need to be careful in interpreting Pi2-band pulsations in the inner magnetosphere.

Van Allen Probes衛星の観測に基づく高エネルギー酸素イオンの深内部磁気圏への動径方向輸送の研究

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Radial transport of high-energy oxygen ions into the deep inner magnetosphere observed by Van Allen Probes

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It is known that proton is main contributor of the ring current and oxygen ions can make significant contribution during major magnetic storms. Ions are supplied to the ring current by radial transport from the plasma sheet. Convective transport of lower-energy protons and diffusive transport of higher-energy protons were reported to contribute to the storm-time and quiet-time ring current respectively [e.g., Gkioulidou et al., 2016]. However, supply mechanisms of the oxygen ions are not clear. To characterize the supply of oxygen ions to the ring current during magnetic storms, we studied the properties of energetic proton and oxygen ion phase space densities (PSDs) for specific magnetic moment (mu) during the April 23-25, 2013, geomagnetic storm observed by the Van Allen Probes mission. We here report on radial transport of high-energy (mu is over 0.5 keV/nT) oxygen ions into the deep inner magnetosphere during the late main phase of the magnetic storm. Since protons show little change during this period, this oxygen radial transport is inferred to cause the development of the late main phase. Enhancement of poloidal magnetic fluctuations is simultaneously observed. We estimated azimuthal mode number less than 5 by using cross wavelet analysis with ground-based observation of IMAGE ground magnetometers. The fluctuations can resonate with drift and bounce motions of the oxygen ions. The results suggest that combination of the drift and drift-bounce resonances is responsible for the radial transport of high-energy oxygen ions into the deep inner magnetosphere. We also report on the radial transport of the high-energy oxygen ions into the deep inner magnetosphere during other magnetic storms.

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Van Allen Probes observations of drift-bounce resonance and energy transfer between energetic protons and poloidal Pc4 wave

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Poloidal Pc4 wave and proton flux oscillation due to the drift-bounce resonance are observed in the inner magnetosphere on the dayside near the magnetic equator by the Van Allen Probes spacecraft on 2 March 2014. The flux modulation is observed in the energy range of 67.0 keV to 268.8 keV with the same frequency of poloidal Pc4 wave. We estimate the resonant energy to be ˜120 keV for pitch angle of 20-40 degrees or 140-160 degrees, and 170-180 keV for pitch angle of 40-60 degrees or 120-140 degrees. The drift-bounce resonance theory gives the resonant energy of 110-120 keV, which is consistent with the observation for small pitch angle, but slightly higher than the observation for large pitch angle. We consider that this discrepancy of the resonant energy is due to the drift shell splitting. In order to examine the direction of energy flow between protons and the wave, we calculate the sign of the gradient of proton phase space density (df/dW) in both outbound and inbound paths. Results showed positive gradient in both paths, which means that the energy is transferred from the protons to the wave. During the appearance of poloidal Pc4 wave, the Dst∗index shows a sudden increase of ˜6.7 nT. We estimate the total energy loss of the ring current from the recovery of the Dst∗index and the variation of proton flux by the drift-bounce resonance. The estimated energy loss is almost comparable for both cases. Therefore, we suggest that the energy transfer from the ring current protons to the wave via the drift-bounce resonance cause the increase of Dst∗index.

Time evolution of radiation belt electrons resonating with chorus and EMIC emissions

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Using results of test particle simulations of a large number of electrons interacting with a pair of chorus emissions, we create Green's functions to model the electron distribution function after all of the possible interactions with the waves [*Omura et al.,* 2015]. Assuming that the waves are generated in a localized range of longitudes in the dawn side, we repeat taking the convolution integral of the Green's function with the distribution function of the electrons injected into the generation region of the localized waves. From numerical and theoretical analyses, we find that electron acceleration process only takes place efficiently below 4 MeV. Because extremely relativistic electrons go through the wave generation region rapidly due to grad-B_0 and curvature drift, they don't have enough interaction time to be accelerated. In setting up the electrons after all interaction with chorus emissions as initial electron distribution function, we also compute the loss process of radiation belt electron fluxes due to interaction with EMIC rising-tone emissions generated in a localized range of longitudes in the dusk side [*Kubota and Omura,* 2017].

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アナログ・デジタル混載ASICによるワンチップ新型プラズマ波動スペクトル受信器の開発

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New type of spectrum plasma wave receiver using one-chip analog-digital mixed ASIC

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Plasma waves are important observational targets for scientific missions investigating space plasma phenomena. In recent missions, fast Fourier transform (FFT) -based receiver is commonly used as a spectrum receiver of the plasma wave instrument. The FFT-based spectrum receiver has advantages in its high time and frequency resolution. In addition, it can share the circuit with a waveform receiver. However, it has a disadvantage in the difficulty of adjusting its receiver dynamic range to the dynamic range of target signals in a wide frequency range, because the expected signal intensities of natural plasma waves strongly depend on their frequency ranges. This disadvantage is also seen in waveform receivers.

In order to overcome this disadvantage of an FFT-based spectrum receiver, we propose a new type of FFT-based spectrum plasma wave receiver that realizes the adjustable wide dynamic range to the expected signal intensities with keeping high time and frequency resolutions. The new receiver measures and calculates the whole spectrum by dividing the observation frequency range into three bands: bands 1, 2, and 3, which span 1 Hz - 1 kHz, 1 kHz - 10 kHz, and 10 kHz - 100 kHz, respectively. The receiver is composed of analog components, analog to digital converters (ADC), FFT module, and controller. Since it requires many analog and digital components, its size becomes large. To reduce the size of the receiver, we develop all analog and digital components as a mixed-signal Application-Specific Integrated Circuits (ASIC) chip.

We have successfully designed all components of the receiver, and we have verified analog components and ADC which developed as an ASIC chip. The dimension of the analog circuit that contains various filters and amplifiers is 4.21 mm x 1.16 mm, and the power consumption is 36 mW. The ADC has a 14-bit resolution and 33 MHz max sampling rate, and its size and power consumption at max sampling rate are 3.2 mm x 0.8 mm and 700 mW, respectively.

In the presentation, we will introduce detailed design and specification of the new spectrum receiver and each component.

プラズマ波動は宇宙電磁環境を解明するために重要な観測対象であり、プラズマ波動受信器は様々な理学衛星に搭載されてきた。プラズマ波動受信器には波形捕捉型・スペクトル型の 2 種類があるが、スペクトル型受信器としては高速フーリエ変換 (FFT) ベースの受信器が近年主に使用されている。FFT ベースのスペクトル型受信器は高い周波数・時間分解能を得られ、波形捕捉型受信器とアナログ回路を共有することができるという利点がある。しかしながら、受信器のダイナミックレンジを観測対象のダイナミックレンジに合わせるのが難しいという波形捕捉型受信器と同様の欠点を抱えている。

我々は、これらの欠点を克服した新型スペクトル受信器を提案している。新型スペクトル受信器は観測帯域を 3 つの周波数帯に分割し、それぞれ別のゲインを設定しダイナミックレンジを調整できるようにすることで上記の問題を解決することができる。現在の設計においては、Band1: 1 Hz - 1 kHz, Band2: 1 kHz - 10 kHz, Band3: 10 kHz - 100 kHz の 3 つのバンドに分割するようになっている。それぞれの周波数帯で波形を順番に測定し、FFT を実行することにより全体のスペクトルを得ることができる。この新型受信器はアナログ回路、A/D 変換器、FFT モジュール及びこれらを制御するコントローラーから構成されるが、必要となる回路が多いためそのサイズが問題となってしまう。そこで我々は、これらのコンポーネントを全てアナログ・デジタル混載 ASIC として実装することにより小型かつ高性能な受信器を実現する。

これまでに、必要となる全てのコンポーネントの設計を完了しており、アナログ回路及び A/D 変換器については ASIC として回路を作成し、その検証も完了している。アナログ回路の面積は 4.21 mm x 1.16 mm であり、消費電力は 36 mW であった。ADC は分解能が 14bit、最大サンプリング速度は 33 MHz であり、面積は 3.2 mm x 0.8 mm、最大サンプリング速度での消費電力は 700 mW であった。

発表においては新型スペクトル受信器と個々のコンポーネントについて、詳細な設計及び、特性について紹介する。

Interaction of ULF waves with different ion species: Pitch angle and phase space density implications

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ULF waves can accelerate/decelerate the charged particles including the ring current ions via drift-bounce resonance, which play an important role in the dynamics of ring current during storm times. This study compares the different behaviors of oxygen ions (10.5-35.1 keV) and protons (0.3-12.3 keV) which simultaneously interact with Pc5 ULF waves observed by Cluster on 3 June 2003. The ULF waves are identified as the fundamental mode oscillations. Both oxygen ions and protons show periodic energy dispersion and pitch angle dispersion signatures, which satisfy the drift-bounce resonance condition of N=2. The different behaviors of oxygen ions and protons include (1) the resonant energy of oxygen ions is higher than that of protons due to mass difference; (2) the phase space density (PSD) of oxygen ions show relative variations (3.6–6.3) that are much larger than that of protons (<0.4), which indicates a more efficient energy exchange between oxygen ions and ULF waves; (3) the PSD spectra show that oxygen ions are

accelerated, while protons are decelerated, which depend on the radial gradient of their PSD; (4) the pitch angle distributions (PADs) of the oxygen ions and protons show negative slope and bidirectional field-aligned features, respectively, which is related to the preexisting state of ion PADs before the interaction with the ULF waves. In addition, the resonant ions with peak fluxes tracing back to the magnetic equator are always collocated with the accelerating (westward) electric field, which indicate that the ions are mainly accelerated near the magnetic equator and the electric field intensity of ULF waves peaks there.

対流の励起とサブストームの発生

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Development of convection to the substorm

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In this paper, we try to elucidate the generation mechanism of the field-aligned current (FAC) and coexisting convection.From the comparison between the theoretical prediction and the state of numerical solution from the high-resolution global simulation, we obtain the following conclusions about the distribution of dynamo, the magnetic field structure along the flow path that diverges Poynting flux, and energy conversion promoting the generation of electromagnetic energy.

The dynamo for the region-1 FAC, which is in the high-latitude-side cusp-mantle region, has a structure in which magnetic field is compressed along the convection path by the slow mode motion. The dynamo for the region-2 FAC is in the ring current region at the inner edge of the plasma sheet, and has a structure in which magnetic field is curved outward along the convection path.

Under these structures, electromagnetic energy is generated from the work done by pressure gradient force, in both dynamos for the region-1 and region-2 FACs. In these generation processes of the FACs, the excitation of convection and the formation of pressure regimes occur as interdependent processes.This structure leads to a modification in the way of understanding the Dungey convection.

Generation of the FAC through the formation of pressure regimes is essential even for the case of substorm onset. Detailed event sequence leading to the substorm onset is reproduced from a high-resolution global MHD simulation. The ionospheric onset does not coincide with neither launch in the midtail nor arrival to the inner magnetosphere of the dipolarization front. The near-earth dynamo due to the squeezing causes the onset before the arrival of the BBF flow from the NENL.

The arrival of flow to the equatorial plane of the inner magnetosphere occurs two minutes after the onset, when the WTS starts to develop toward the west. The expansion phase is further developed by this flow. Looking at the present result that the onset sequence induced by the near-earth dynamo reproduces the details of observation quite well, we cannot avoid to conclude that the current wedge (CW) is a misleading concept.

対流は、ダイナミクスと散逸から構成される。さらにダイナミクスは、磁気圏ダイナミクスと電離圏対流から構成される。磁気圏ダイナミクスは、流れ場、圧力場、凍結の原理から成り、力バランス、ダイナモとポインティングフラックスの発散構造を内包する。ダイナモの励起のため、エネルギー変換が必要であり、ポインティングフラックスの発散のため、slow mode の運動が必要である。電離圏対流は、磁気圏ダイナミクスから生成される FAC の closure であり、ダイナモに対応するエネルギーの sink である。ダイナミクスによって磁場の運搬、変形が進展すると、対流の流線に沿って磁場がトポロジーを変えることが必要となり、散逸によるトポロジー変更が顕在化する。

良く知られている Dungey 対流は、マグネトシース流の減速でダイナモを励起し、反平行リコネクションで散逸を与える構成になっている。ところが最近の研究で、これらは誤りであり、ダイナモは圧力によって励起され、散逸はヌルによって与えられることが分かってきた。反平行リコネクションも 2 次元のヌルであるが、実際の散逸は 3 次元ヌルで発生する。３次元では、セパレーターライン上の平行リコネクションとなる。

観測では対流の全体が見えないので、その理解を誤っても直接困ることは起きないように感じる。しかし対流の理解を誤ると、それがサブストームの誤った解釈に至るという致命的な欠陥を引き起こす。その典型が反平行リコネクションによる太陽風からのプラズマ流入（成長相）と、急な反平行リコネクションや不安定の発生によるオンセットの解釈であろう。これらは誤った Dungey 対流からの誤った推論と言える。

太陽風―磁気圏相互作用では、ポインティングフラックスの流入が主役である。ただし過渡状態ではプラズマも侵入する。昼側ヌル-セパレーター構造によって発生する開磁場は、カスプ付近で局所的にマグネトシースプラズマを加速し、これが減速する時ポインティングフラックスをカスプ内に注入し、カスプの圧力を上昇させる。マグネトシース内の圧力傾度を過る流れも、同様な作用を行う。これらのポインティングフラックスは、CF 電流によって運ばれる。生成された磁気圏内の圧力が、slow mode expansion を通じて、カスプーマントル領域で R1FAC を励起する。ポインティングフラックスは、テーター電流によって、プラズマシートにも運ばれ、プラズマシートの圧力分布を生成する。プラズマシートも圧力ダイナモであり、力バランスと自己無撞着構造を形成し、R2FAC を生成する。

ヌル-セパレーター構造は、IMF の向きによって、大きく変化し、IMF が南向きになると成長相が進行する。成長相の対流で、昼側ヌルから別のヌルが分離し、フランクに沿ってテイル側に移動する。両者は X-ラインで結合されている。成長相では対流はプラズマシートに侵入せず、プラズマシートの thinning によって磁場構造の変形が吸収され、磁気圏ダイナミクスが進展する。この構造はプラズマシート境界にシアーを伴い、quiet arc が発生する。テイルヌルは、２次のヌルであり、プラズマシートで磁場構造の変形が吸収できなくなると、プラズモイド、core By、２巻き磁場、近尾部の NENL を生成する。この夜側ヌル-セパレーター構造については、まだ理解が完全でない。

NENL に伴い対流はプラズマシート内に侵入し、過渡的に、dipolarization front やインジェクションと見える変動を引き起こす。インジェクションは過渡的圧力領域の生成であり、近球近傍ダイナモとして作用し、initial brightening を引き

起こす。インジェクションは力バランスの変更を伴う状態遷移であり、散逸の発生と協同している。双極子化はこの力バランスの変更の現れである。力バランス変更の結果、内部磁気圏の圧力が上昇し、部分環電流となって R2FAC が増大する。

サブストーム拡大相オンセット時におけるエネルギーの流れと変換過程

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Pathway and conversion of energy at substorm expansion onset

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Substorm expansion onset is a long-standing unsolved issue in magnetospheric physics. One of the central issues is abrupt intensification of upward field-aligned current (FAC) that is responsible for accelerating electrons downward and emitting bright aurorae. Based on the results obtained by the global magnetohydrodynamics (MHD) simulation, we present energy flow and energy conversion associated with the upward FACs that manifest the onset of substorm expansion. The cusp/mantle region transmits electromagnetic energy to almost the entire region of the magnetosphere. A part of electromagnetic energy is stored in the lobe in the growth phase. When reconnection takes place in the near-Earth tail region, the stored energy is released in addition to the continuously supplied one from the cusp/mantle dynamo. Two types of pathways of energy seem to be involved in the generation of the onset-associated FACs. The first type is related to the earthward fast flow associated with reconnection on the nightside. The electromagnetic energy coming from the lobe splits into the thermal energy and the kinetic energy. The kinetic energy is then converted to the thermal energy and the electromagnetic energy, in association of flow braking. The second type is that the plasma coming from the lobe goes into the inner magnetosphere directly. The electromagnetic energy is converted to the thermal energy, followed by the electromagnetic energy at off-equator. The near-Earth dynamo region, where the electromagnetic energy is generated, seems to be embedded in the convection system. In this sense, the expansion onset may be regarded as a sudden, local intensification of the convection.

ホースカラーオーロラとシータオーロラ：シミュレーションと観測の比較

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Hose-collar Aurora and Moving Theta Aurora: Simulation and Observation

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Hose-collar aurora is one of the manifestation of the sun-aligned polar car arcs for constant IMF By and positive Bz. The narrowed polar cap is associated with bordered morning and evening sides sun-aligned arcs. The horse collar region and the void will be relatively steady phenomenon on a global scale. We have examined the results of MHD simulation for the case of constant IMF By during northward IMF condition. Results demonstrate that plasma sheet has been inclined due to the IMF By, which leads to the expansion of morning side auroral oval into the northern polar cap for IMF By <0. In the simulation, we have newly found the bulge structure, which is the expansion of evening side auroral oval in the northern polar cap region. We further found i) vertical closed magnetic field lines, connecting the both hemisphere in the evening sector and ii) field aligned current structure, elongated sun-aligned direction.

On the contrary there appears an arc forming a single large-scale bar in the central polar cap. This aurora is known as the theta aurora. The theta aurora is a phenomenon associated with a switch of the IMF By during northward IMF condition. The theta aurora is non-stationary, although the appearance of the arc itself is similar to sun-aligned arcs. We have examined the results of MHD simulation for the case of IMF By polarity change. The trans polar arc appears in the morning sector in the northern polar cap and it moves dusk ward as time goes on. In this stage, the polar cap and tail lobes are continuously encroached by the new open field lines connected to the new IMF. Whereas magnetic field lines accumulated in new lobes tend to rotate the outer plasma sheet in the opposite direction, the old merging-cell convection still continues to generate closed field lines that must return to dayside against the new-lobe formation. The growth of new lobes results in the blocking of the return path toward dayside of closed field lines generated in the old merging cell to form the kink structure in the plasma sheet. Losing their return path, these closed field lines generated from old lobes accumulated on the night side and leads to the formation of theta aurora.

In the talk, we will compare simulation results with observations for the hose-collar aurora as well as the theta aurora.

サブストームMI結合のもうひとつのシナリオ：電離層ドライバー

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A new scenario for substorm MI-coupling : An ionospheric driver

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A new scenario of substorm MI-coupling is proposed, in which transient westward electric fields transmitted from the magnetosphere build up a stable negative potential region in the auroral zone ionosphere through differences in the mobility of collisional ions and collisionless electrons. Field-aligned currents are generated from the negative potential region in the ionosphere to accomplish the MI-coupling. The ionospheric driver proposed here is distinguished from the magnetospheric source of the field-aligned currents.

Build up of the negative potential region in the ionosphere is affected by the ion-neutral and electron-neutral collisions in the ionosphere. This means that the onset timing and following development of auroras may differ in the individual ionosphere, even if the uniform electric fields are transmitted from the magnetosphere.

サブストームにかかわる磁気圏－電離圏結合回路は磁気圏に蓄積された力学的エネルギーを地球電離圏に開放する役目を持つため、磁気圏に電源、電離圏に負荷をもつCurrent Wedge電流系やBostrom電流系が提案されている。しかしながら、これらのモデルは力学的な条件を満たしていないため具体性を欠いていると指摘されている　[田中、南極資料、2014]。

ここでは、発想を変えて全く異なる視点から磁気圏－電離圏結合を考えてみたい。

要点は、まずDipolarizationにかかわる局所的な西向き電場が磁場沿いに磁気圏より電離圏へ侵入する事であり、次にそれによるローレンツ力がCollisionless electronとCollisional ionからなる電離圏内で安定的に負電荷を集積する事である。負の電荷の周りには正の電荷が分布するため、外側にDownward、内側にUpwardの沿磁力線電流が同心円状に発生する。力学的にはこの電流系のドライバーはオーロラ帯に侵入する西向き電場であり電離層は負荷としての役割を果たすであろう。同心円状の沿磁力線電流系が磁気圏－電離圏結合回路となる。

このモデルの特徴はトリガーとなる電場は磁気圏から伝えられるものの、オーロラあるいは磁場変動に直接かかわる電場は電離層内で集積された負電荷がもたらす事である。電荷の集積には荷電粒子と大気との衝突が影響するため、仮に一様な電場が伝えられても個々の電離層では異なるオーロラが見られるであろう。

New Interpretation of PBI: Can the ionospheric polarization FAC induce explosive electron acceleration?

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A new idea for interpretation of the poleward boundary intensification(PBI) of aurora emission is proposed by Ohtani and Yoshikawa [2016]. In their model, as the polar cap flow approaches the auroral oval, field aligned currents (FACs)are induced by the polarization effect at the poleward boundary of auroral oval because of divergence of ionospheric current accompanied by the polar cap flow at the steep gradient of conductivity. Their model could explain some features of PBIs summarized by Zou et al., [2014] such as horizontal extension of PBIs along the boundary of auroral oval. According to the Ohtani and Yoshikawa [2016], ionospheric polarization can produce upward FACs enough to explain the PBIs in amplitude of current density. However, the ionospheric E-layer is filled with cold and dense plasma, an expected downward electron velocity accompanied by polarization FAC of an upward shear Alfven wave is only the order of several tens of m/sec, which alone has a difficulty in explaining auroral emission of PBIs.To understand a generation process of PBIs of auroral emission, we need to clarify the acceleration process of downward electrons during shear Alfven wave excited by the polarization effect, is propagating to the magnetosphere from the ionosphere. In this study, we consider the kinetic process of electron acceleration during shear Alfven wave crossing the density cavity region just above the ionosphere, which are characterized by the steep gradients of the Alfven velocity and electron inertial length. We will discuss how the generation process of super Alfvenic electrons by the inertial Alfven wave at the electron cavity region can be applied to the PBIs of auroral emission.

Formation and Development of Poleward Boundary Intensifications of Auroral Emission

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The present study is motivated by a recently proposed idea that the poleward boundary intensification (PBI) of auroral emission is an effect of electrostatic polarization. As the fast polar cap flow approaches the auroral oval, field-aligned currents (FACs) are induced at the poleward boundary because of the steep gradient of ionospheric conductance, which may be associated with the formation or intensification of an auroral form. In this study we examine four PBI events and address how well the observed longitudinal extension and associated current systems can be explained in terms of ionospheric polarization. The observations are summarized as follows: (1) the PBIs actually take place equatorward of the open-closed boundary; (2) the PBIs are collocated with an upward FAC, which closes with an adjacent downward FAC through the ionosphere forming a longitudinally extending convection channel; (3) the PBIs extend longitudinally in the same direction as the longitudinal convection; (4) the PBIs extend both eastward and westward immediately following the arrival of the fast polar cap flow; (5) in one event ground magnetic variations can be explained by a moving upward FAC, which suggests that the current system associated with the PBIs is not unique. Whereas caution needs to be exercised in generalizing these results, they suggest that the ionospheric polarization plays an important role in the formation and evolution of the PBIs. It is also suggested that the spatial development of the PBIs may be preconditioned by preceding auroral activity and preexisting ionospheric convection.

Application of a global magnetospheric-ionospheric current model for dayside and terminator Pi2 pulsations

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Pi2 magnetic oscillations on the dayside are considered to be produced by the ionospheric current that is driven by Pi2-associated electric fields from the high-latitude region, but this idea has not been quantitatively tested. The present study numerically tested the magnetospheric-ionospheric current system for Pi2 consisting of field-aligned currents (FACs) localized in the nightside auroral region, the perpendicular magnetospheric current flowing in the azimuthal direction, and horizontal ionospheric currents driven by the FACs. We calculated the spatial distribution of the ground magnetic field produced by these currents using the Biot-Savart law in a stationary state. The calculated magnetic field reproduced the observational features reported by previous studies; (1) the sense of the H component does not change a wide range of local time sectors at low latitudes; (2) the amplitude of the *H* component on the dayside is enhanced at the equator; (3) The *D* component reverses its phase near the dawn and dusk terminators; (4) the meridian of the *H*-component phase reversal near the dusk terminator is shifted more sunward than that near the dawn terminator; (5) the amplitude of the *D* component in the morning is larger than that in the early evening. We also derived the global distributions of observed equivalent currents for two Pi2 events. The spatial patterns of dayside equivalent currents were similar to the spatial pattern of numerically derived equivalent currents. The results indicate that the oscillation of the magnetospheric-ionospheric current system is a plausible explanation of Pi2s on the dayside and near the terminator. These results are included in an accepted paper by Imajo et al. [2017, JGR].

Effects of Ionospheric Hall Polarization Field on Magnetospheric Structure and Dynamics in Global MHD Simulation

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In some settings and parameterizations in global MHD magnetosphere models, we especially place importance on the descriptions for low-altitude region, that is, the magnetosphere-ionosphere (M-I) coupling and boundary conditions imposed on MHD variables, and we expect that they largely control the M-I system. In order to advance our understanding of the M-I system from the viewpoints of the above interest and to simulate accurately the magnetosphere, we are investigating the responses of magnetosphere for different treatments of low-altitude region.

The science question of the present study is how and in what way the ionospheric Hall polarization field generated by the Hall conductance inhomogeneity impacts the convection and dynamics in the magnetosphere. The background of this challenge is a recently proposed concept of ionospheric control based on generalized theory for ionospheric polarization/Cowling channel formations [*Yoshikawa et al.*, 2008; 2013; 2017]. This challenge is important for practical use as well because at the present uncertainties in the conductance estimation remains both in the observational and simulation studies.

We perform simulations for the following pairs of conductance setting and upstream boundary conditions. As for the conductance setting, we test four cases; Hall part of conductance set by R_H = 3.5 (the default setting), 2, 5, and uniform distribution (1.0 [S]), where R_H is the ratio of Hall to Pedersen conductance. As for the upstream condition, we test three cases of IMF-By polarity; positive, negative, and 0-By. The solar wind parameters and IMF-Bz are common to all cases. IMF-Bz is changed from northward to southward during the course of simulation runs.

The results are summarized as follows.

(a) Asymmetry / symmetry of the large-scale structure: As for the cases of uniform Hall conductance, the magnetosphere is completely symmetric with respect to both the XY and XZ-planes under 0-By. Under the finite IMF-By, the magnetosphere shows asymmetry consistent with the By-polarity. As for the cases of non-uniform Hall conductance, the magnetosphere shows global asymmetry even under the condition of 0-By. The asymmetry becomes severe for larger R_H. This result indicates that the ionospheric Hall polarization field obviously one of the important factors to deform the magnetospheric structure.

(b) Location and timing of the Near-Earth Neutral Line formation: Location becomes closer to the earth and timing becomes earlier for larger R_H, compared to the cases of uniform Hall conductance. The deference seems to be related to combined effect of twist of magnetic field lines due to the Hall polarization field and energy/current closure between the magnetosphere and ionosphere.

(c) Near-earth convection field during the growth phase: In the cases of non-uniform Hall conductance, an inflection structure of equatorial convection is formed around premidnight sector inside R = 10 R_E. Considering that the region 2 FAC is not sufficiently developed in MHD models, the structure is considered to be a convection reversal often shown in the Rice Convection Models. Previous studies regard the structure as Harang Reversal in the magnetosphere. On the other hand, in the case of uniform Hall conductance with 0-By, such structure is not formed and the convection is completely symmetric. This result indicates that Harang Reversal may not be formed without the effect of ionospheric Hall polarization field.

The above initial research strongly suggests that the ionospheric Hall polarization plays a significant role in the M-I system definitely. In this presentation, we will report the detailed analysis for the above items.

非一様磁場中でのアルヴェン波を介した磁気圏-電離圏結合の理論解析

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Theoretical analysis of the magnetosphere-ionosphere coupling via Alfven waves in non-uniform magnetic field

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To clarify a spontaneous formation process of auroral arcs, we have carried out theoretical and numerical analyses and simulations of the magnetosphere-ionosphere coupling based on the feedback instability which has been applied to a variety of magnetic field configurations, such as the simple uniform field, the dipole field, and the magnetic field sheared by large-scale field-aligned currents. Numerical analysis of the feedback instability in case with the sheared field has shown increase of the field-line-resonance (FLR) frequency in a high wavenumber region as well as enhancement of the instability growth rate. The increase of the resonance frequency is roughly explained by an analytic solution of the damped oscillation, while its detailed behavior in a weak shear case is still an open issue. In the present study, we have applied a perturbative analysis to the eigenvalue equation of FLR which enables us to accurately estimate the resonance frequency. We would discuss the detailed results including its application to the dipole configuration.

オーロラアークの自発的構造形成過程を明らかにするため、これまでフィードバック不安定性にもとづいた磁気圏-電離圏結合系の理論・数値解析や非線形シミュレーションが進められてきた。この理論モデルは、単純な一様磁場配位から、双極子磁場配位、さらに、大規模沿磁力線電流によるシア磁場配位に適用されてきた。シア磁場下での数値解析では、フィードバック不安定性の成長率の増大とともに、高波数領域において磁力線共鳴周波数の変化が見出された。この共鳴周波数の変化については、減衰振動を与える解析解により磁気シアに対する大まかな傾向が説明されるが、シア磁場の弱い場合のより詳しい振る舞いは再現できなかった。本研究では、固有値方程式に摂動論的解析を適用し、共鳴周波数の正確な見積もりが可能となった。講演では双極子磁場配位への適用も含めて詳細な議論を行う。

FF-MIT: A Formation Flight Mission by Innovative Compact Satellites Exploring the Magnetosphere-Ionosphere-Thermosphere Couplings

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We are planning to launch the first Japanese formation flight satellite mission for quantitatively investigating the terrestrial magnetosphere-ionosphere-thermosphere coupling mechanisms, namely the MIT system. The recent progress and latest status of this mission, so-called FF-MIT, will be shown in this presentation. FF-MIT would be carried out on the basis of integrated in-situ and remote-sensing observations using 2-4 compact/micro satellites in a polar orbit at altitudes of about 300-4000 km. The most important science target of FF-MIT is the demonstrative and quantitative investigation concerning the physical processes and mechanisms controlling the space-Earth connections, represented by the MIT system. The observational objectives of FF-MIT could be listed as follows: (a) Transports and conversions of plasma and electromagnetic energies across the space-Earth boundaries, (b) Planetary/space plasma accelerations and mass escape via the wave-particle interactions, (c) Response of the neutral atmosphere to space plasma activities via the plasma-neutral interactions. The satellite and instrumental configuration/specification and the cluster launch capability/strategy by an Epsilon rocket of JAXA would be clarified and fixed within a year in the framework of the FF-MIT working group, which will be proposed in this year to ISAS/JAXA. We have already made some of fundamental assessments of the technical feasibilities on the mission scenario and the instrumental specification/development, particularly regarding some crucial technical subjects with engineering groups in JAXA and design/fabrication teams in manufacturers. This paper will be devoted also to address the updated results obtained in these engineering activities, for instance, the possibility of the orbit insertion for the multiple compact satellites by a single Epsilon launch, the formation flight configuration and its control by satellite propulsion system, the attitude control required for the mission objectives. We are also expanding the possibilities of substantial international collaborations, for instance with EISCAT_3D and ALIS_4D. We would like to start the pre-project (phase-A study) of the FF-MIT mission in a year in order to realize the fascinating demonstrative research based on the cutting-edge space measurements and the powerful ground-based observations in mid 2020s.

「すざく」衛星によるコロナ質量放出に伴う地球外圏からの広がったX線放射の観測

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Suzaku observation of terrestrial diffuse X-ray emission associated with coronal mass ejection

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We report on Suzaku observation of terrestrial diffuse X-ray emission associated with coronal mass ejection (CME). X-rays from the Earth are emitted form two regions and by different mechanisms (Bhardwaj et al. 2007). One is bremsstrahlung emission by accelerated electrons in the polar regions. The other is line emission from the whole atmosphere surrounding the Earth. The line emission is caused by scattering of solar X-rays and solar wind charge exchange (SWCX) between solar wind ions and exospheric atoms. Since SWCX occurs even in tenuous atmosphere such as planetary atmospheres, we can explore the Earth's exosphere and magnetosphere.

In order to explore the terrestrial environment from SWCX emission, we analyzed all the Suzaku archival data to find an event where strong enhancement is accompanied by the passage of CMEs (Ishikawa Ph. D thesis 2013, Ishi et al. 2016). Associated with the M-class solar flare on 2013 April 11, CMEs occurred and reached the Earth on April 13. However, the SWCX emission delayed from about 1 day from the arrival of CMEs, suggesting that more ions are contained in the magnetic cloud than the inside of CME shock waves. In addition, we confirmed strong emission lines from magnesium and silicon in addition to oxygen and carbon seen in most solar winds. It may be derived from high temperature plasma heated by solar flare. We discuss these results in the context of the plasma transport process in the magnetosphere.

本講演では、X線天文衛星「すざく」で観測されたコロナ質量放出 (Coronal Mass Ejection, CME) に伴う地球大気からの広がったX線放射について報告する。地球からのX線は大きく分けて二つの領域から異なるメカニズムで放射されている (Bhardwaj et al. 2007)。一つは極領域からの加速された電子による制動放射、もう一つは大気全体からの太陽X線の散乱、太陽風イオンと大気原子の電荷交換 (Soalr Wind Charge eXchange, SWCX) による輝線放射である。SWCX 放射は惑星大気のような希薄なガスにも反応するため、地球の外圏や磁気圏などの周辺環境を探る新たな鍵として注目されている。

我々は SWCX 放射から地球の周辺環境を探るために「すざく」衛星の公開データを解析し、CME 通過に伴う SWCX 放射の強い増光が見られるデータを発見した (Ishikawa Ph. D thesis 2013, Ishi et al. 2016)。2013 年 4 月 11 日に発生した M クラスのフレアと同時に地球方向への CME が観測され、2 日後の 13 日にその影響が地球に到来した。しかし、SWCX 放射は CME 到来から約 1 日遅れた変動を示していた。これは CME の高温高密度である衝撃波内側よりも、低温低密度である磁気雲中にイオンが多く含まれていることを示唆している。さらに、増光により生じたスペクトルを解析した結果、通常の太陽風中に含まれている酸素や炭素などのイオンからの輝線の他に、マグネシウムやシリコンなどの重イオンからの輝線を確認した。フレアにより加熱された高温プラズマに由来している可能性がある。磁気圏内のプラズマ輸送過程など含め、これらの結果について議論する。

地磁気共役点でのプロトンオーロラの振り込みエネルギー推定

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Estimation of precipitating energy of proton aurora at geomagnetic conjugate points

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Intensity of proton aurora is weaker than that of electronic aurora so that observation of proton aurora is difficult. However, due to improvement in the sensitivity of observation instruments, observations of proton aurora have been increasing. Observation of proton aurora at geomagnetic conjugate points was carried out by using a scanning photometer at Iceland and Showa Station by Sato et al. [1986], who measured intensities of H-beta 486.1 nm along geomagnetic meridians. However, there are no observations after that. For this reason conjugacy, an emission intensity ratio of both hemispheres, and spatial /temporal relationship of proton aurora with the electron aurora have not yet been studied.

Observation of proton aurora is more difficult than that of electron aurora, because it is much weaker than electron auroras, which can be contamination in observation of proton aurora. We tried to estimate intensities of proton aurora from all-sky images of proton aurora and its background obtained at Showa Station, but we found it very difficult to strictly extract intensities of proton aurora. To estimate intensities of proton aurora by eliminating background of electron aurora spectral observation is required. Therefore, we have developed a Proton Aurora Spectrograph (PAS) which measures proton aurora along a geomagnetic meridian.

PAS has a narrow field-of-view along a geomagnetic meridian of 180 degree, which is accomplished by a variable-width slit placed at the focal plane of an all-sky optics. Light that passes through the slit is converted to a parallel beam and fed into a transmission diffraction grating. Then a space vs wavelength image is projected on a CCD with 1024 $*$1024 pixels. Pixel counts are increased by 2 $*$2 pixel binning. PAS is designed to observe a wavelength range from 417 nm to 579 nm with a spectral resolution of 1.9 nm. N_{2+} 427.8 nm and OI 557.7 nm as well as H-beta 486.1 nm are included in this spectral region. PAS was installed at the optical observation site at Tjornes in Iceland which is one of a pair of geomagnetic conjugate points in early September 2016. In addition, it will be also installed at Showa Station in 2017(2018) and will start conjugate point observation. Observation by PAS in Iceland started on September 27, 2016, and ended on April 26, 2017. An image was obtained every 3 min with an exposure time of 177 sec from September 27, 2016 to December 8, 2016 and every 1 min with an exposure time of 55 sec from December 12, 2016. The change in the exposure time is due to increase of sensitivity by updating the CCD camera.

It is possible to estimate energy of precipitating protons by the Doppler shift amount of proton aurora emissions. During this observation period, more than 10 events of proton aurora are identified. We estimated the temporal change of brightness at 486.1 nm, 427.8 nm, and 557.7 nm and the temporal change of energy of precipitating protons using image data obtained during the last season. The results will be introduced in the presentation, and its interpretation will be discussed. For the data obtained the last season we have found two problems. One is inhomogeneity of sensitivity the zenith angle. This arose from difficulty in adjusting the width of variable slit to be constant. Another is insufficient spectral resolution to obtain an energy distribution of precipitating protons. Then, a fixed width slit will be introduced to PAS in Iceland. Geomagnetic conjugate observation of proton auroras will be conducted from March 2018 at Tjornes in Iceland and Showa Station.

プロトンオーロラの発光は電子オーロラと比較すると弱く、観測は難しい。しかし観測機器の感度の向上により、その観測例も増えはじめている。一本の磁力線で繋がる二地点 (地磁気共役点) でのプロトンオーロラの観測は、Sato ら [1986] によるアイスランドと南極昭和基地においてフォトメーターを用いて波長 486.1 nm の水素バルマーベータ線 （H β 線）の子午線方向の地磁気共役点観測を行った以後例がなく、プロトンオーロラの共役性の有無、両半球の発光強度比、電子オーロラとの空間的・時間的な関係といった点はまだわかっていない。

プロトンオーロラの観測で問題となるのは、発光の弱さと発光に混じる電子オーロラの発光である。昭和基地で得られた全天イメージャーによるプロトンオーロラとそのバックグラウンドの画像データを用いてプロトンオーロラの抽出を試みたが、プロトンオーロラの発光のみを厳密に抽出することは非常に困難であることが分かった。プロトンオーロラの発光を厳密にバックグラウンドから取り出すにはスペクトルを取得することが必要である。そこで、地磁気子午線に沿ったプロトンオーロラ発光の抽出を目指して Proton Aurora Spectrograph(PAS) を製作した。

PAS は、全天観測用の光学系にスリット、回折格子を組み込むことで視野内に光を分散させることを可能とした分光観測機器である。PAS は地磁気子午線に沿った南北 180 度の細い視野を持ち、空間一次元、波長一次元の画像を取得する。この画像のサイズは 1024$*$1024 pixels で、感度を高めるために 2$*$2 pixels のビニングを行っている。観測波長範囲は 417 nm から 579 nm で、H β 線（486.1 nm）の他、窒素分子イオン 427.8 nm と酸素原子 557.7 nm の発光が同時に取得できるようになっている。また、波長分解能は 1.9 nm である。PAS はまず 2016 年 9 月初めに共役点のペアの一方となるアイスランド・チョルネスに設置された。2017 年度に南極・昭和基地にも設置され、共役点観測を実現する予定である。先んじて設置されたアイスランドの PAS では、2016 年 9 月 27 日から 4 月 26 日まで観測を行った。観測は 2016 年 9 月 27 日から 2016 年 12 月 8 日までは 177 秒の露光時間で 3 分ごとに、2016 年 12 月 12 日から 2017 年 4 月 26 日までは 55 秒の露光時間で 1 分ごとに画像を取得した。この露光時間の変化は 2016 年 12 月にカメラを交換したことで感度が

上昇したことによるものである。
PAS によって得られたプロトンオーロラスペクトルのドップラーシフト量から注入プロトンのエネルギーを推定することが可能である。この観測期間中で、プロトンオーロラのイベントは 10 以上確認できている。今回は、このシーズン中のデータを使用し、各日の 486.1nm、427.8 nm、 557.7 nm での発光の時間変化と、エネルギー推定値の時間変化を推定した結果につて考察する。昨シーズンの観測では、可変スリットの幅を一定に調節するのが困難で、天頂角に対して感度が一定ではないという問題、プロトンのエネルギー推定をするためにはスペクトル分解能が不足しているという問題が明らかになった。それらの問題を解決するために、スリットを固定幅のスリットに交換した。2018 年 3 月の共役点観測シーズンから、アイスランド・昭和基地での同時プロトンオーロラ観測が実現する。

高速オーロライメージャのトリガリングシステムの開発

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Development of triggering system for ground based high-speed aurora imagers

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Ground-based High-speed Aurora Imagers (HAIs) have been deployed worldwide and it is important to synchronize the clocks at remote stations, such as geomagnetic conjugate stations of Syowa station, Antarctica and Tjornes, Iceland. It is therefore necessary to assure the timestamp of every image within the error of millisecond order for the best data comparison at conjugate positions.

New controlling system is proposed using a newly developed triggering circuit board called "UTC-board" for Hamamatsu EMCCD and sCMOS cameras, which is playing important roles as the ground-based support observation of ERG project. Observation using this system achieved time stamp accuracy within 3.125 milliseconds (imaging at 320 frames per second). The design specification guarantees the timestamp accuracy within 11 microseconds and is applicable to high speed observations with higher time cadence in the future.

We introduce the analysis results of the time fluctuation of pulsating aurora simultaneously observed at the magnetic conjugate point between Iceland and Syowa Station using this system. The success of developing and installing the new triggering system leads to high reliability of time based analysis and robustness of timestamps with less data gaps for ground-based HAI data.

高速オーロライメージャ（HAI）が世界各地に配備され始めた。特に南極・昭和基地とアイスランド・チョルネスの地磁気共役点といった遠隔地の観測地点においては、時刻を同期させた観測を行う事が重要である。地磁気共役点のデータを正確に比較するためには、得られる全ての画像について、タイムスタンプの精度をミリ秒のオーダーで保証することが必要となる。

浜松ホトニクス製の EMCCD と sCMOS カメラ用に新たに開発したトリガ回路基板“ UTC-board ”を用いて、ERG プロジェクトの地上支援観測として重要な役割を果たす、正確に同期した観測を行う新しい制御システムを開発した。このシステムを使用した観測で、3.125 ミリ秒（320 フレーム/秒での撮像）以内のタイムスタンプの精度を達成した。設計仕様として 11 マイクロ秒以内のタイムスタンプ精度が保証されており、将来的により高速な撮像観測にも使用できる。

2017 年 3 月 6 日に、アイスランドと昭和基地の磁気共役点で、新しい観測システムを用いて同時に観測された脈動オーロラの時間変動の解析結果を紹介する。新しいトリガシステムの開発と観測器への導入により、時刻を用いた HAI データの分析の信頼性とタイムスタンプの堅牢性を高めることが出来た。

Pc 5オーロラアーク脈動の地上・衛星同時観測

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Ground-space coordinated observations of Pc 5 auroral arc pulsations

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Morphological signatures of Pc 5 auroral arc pulsations observed on the ground are as follows: 1) East-west-aligned auroral arcs elongated ~1000-3000 km, 2) Luminosity pulsations associated with poleward moving pulsation with recurrence period of ~2-10 minutes (Pc 5 range), 3) Occurrence region is located at just the poleward side of commonly observed pulsating aurora in the post midnight sector (occurrence peak is ~03 MLT), 4) Auroral structure is band-type diffuse aurora, 5) Luminosity is much higher than pulsating aurora, 6) Ground-based magnetic field variations (Pc 5 magnetic pulsations) are associated with the luminosity pulsations. We also examined the data obtained by the THEMIS spacecraft whose footprint traversed near the region of Pc 5 auroral arc pulsations observed on the ground. Particle and field characteristics observed by the spacecraft are as follows: 1) Electric field variations and plasma velocity modulations show one to one correlation with the Pc 5 auroral luminosity pulsations, 2) Magnetic field variations also show the same periods but the wave form is not so clear as that of electric field and plasma velocity variations, 4) Occasionally electron flux shows the same modulation. In this study we will examine in more detailed characteristics of Pc 5 auroral arc pulsations and their related phenomena using the data obtained by the ground-space coordinated observations. Then we will discuss the generation mechanism of Pc 5 auroral arc pulsations.

THEMIS衛星を用いた地球近傍磁気圏における磁気圧・プラズマ圧変動の位相関係の統計的研究

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Statistical study of phase relationships between magnetic and plasma thermal pressures in the near-earth magnetosphere

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The auroral finger-like structures appear in the equatorward part of the auroral oval in the diffuse auroral region, and contribute to the auroral fragmentation into patches during substorm recovery phase. In our previous presentations, we reported the first conjugate observation of auroral finger-like structures using the THEMIS GBO cameras and the THEMIS satellites, which was located at a radial distance of ~9 Re in the dawnside plasma sheet. In this conjugate event, we found anti-phase fluctuation of plasma pressure and magnetic pressure with a time scale of 5-20 min in the plasma sheet. This observational fact is consistent with the idea that the finger-like structures are caused by a pressure-driven instability in the balance of plasma and magnetic pressures in the magnetosphere. Then we also searched simultaneous observation events of auroral finger-like structures with the RBSP satellites which have an apogee of 5.8 Re in the inner magnetosphere. Contrary to the first result, the observed variation of plasma and magnetic pressures do not show systematic phase relationship. In order to investigate these phase relationships between plasma and magnetic pressures in the magnetosphere, we statistically analyzed these pressure data using the THEMIS-E satellite for one year in 2011. In the preliminary analysis of pressure variation spectra, we found that out of phase relationship between magnetic and plasma pressures occupied 40 % of the entire period of study. In the presentation, we will discuss these results in the context of relationships between the pressure fluctuations and the magnetospheric instabilities that can cause auroral finger-like structures

オーロラキロメートル放射とオーロラ極方向拡大との関係：Geotail衛星と地上全天観測

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Auroral kilometric radiation and poleward expansion: Geotail and all-sky observations

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Auroral breakup is characterized by auroral brightening and poleward expansion (PEX). At the time of auroral breakup, the auroral kilometric radiation (AKR) is intensified at hundreds of kilohertz and this frequency range often expands down to tens of kilohertz. These high- and low-frequency AKRs are sometimes separated by a few minutes. However, there is a controversy on whether this high- or low-frequency AKR corresponds to PEX in global images, presumably because of the limited sensitivity of global images.

In this study, we identified PEX using ground-based all-sky images and compare it with AKR observed by the Geotail satellite. We first identified an auroral breakup at 1941:18 UT +- 41 s on 10 March 1999 using global images taken by the Polar satellite. A corresponding traveling compression region was observed at 1941 UT by the Geotail satellite located at 30 Re down the tail, indicating that magnetic reconnection occurred. We then studied corresponding all-sky images taken at Kevo observatory (66.2 magnetic latitude, Finland). As a result, the auroral breakup was identified at 1941:00 UT, and the PEX was ongoing at 1941:40 UT. In contrast, Geotail observed high- and low-frequency AKRs respectively at ˜1941:20 UT and 1942:40 UT.

These observations indicate that PEX corresponds to the high-frequency AKR, not to the low-frequency AKR, which was initiated at least 1 min after PEX. At the beginning of the low-frequency AKR, another aurora was initiated equatorward from the poleward boundary of the auroral bulge. However, this intense auroral did not move poleward but equatorward. These results indicate that the low-frequency AKR does not necessarily correspond to the beginning of PEX, but essentially implies the initiation of intense aurora.

オーロラの爆発的な増光（オーロラ爆発）は、光学的にはオーロラの極方向拡大 (poleward expansion, PEX) を特徴とする。オーロラ爆発は、電波（auroral kilometric radiation, AKR）の人工衛星観測によってもモニターされる。オーロラ爆発開始時には、AKR が強まり、また周波数帯が高周波（数 100 kHz）から低周波数（数 10 kHz）まで広がることが特徴である。この高周波 AKR と低周波 AKR の開始は、数分程度の時間差を持つことがある。両者のどちらが衛星グローバル画像の PEX と対応するかは、過去の研究において異なる解釈がなされてきた。この相違は、衛星グローバル画像では、時空間分解の制限のために、PEX の詳細が不明瞭なためであると思われる。

本研究では、地上全天オーロラ観測を用いることにより、PEX を詳細に同定し、ジオテイル衛星が観測した AKR との比較を行った。まず、Polar 衛星のグローバル画像を用い、オーロラ爆発開始を 1999 年 3 月 10 日の 1941:18 UT +- 41 s と同定した。この時、磁気圏尾部 30 地球半径に滞在していた Geotail 衛星が、traveling compression region を 1941 UT に観測したため、尾部磁気再結合が生じていたと考えられる。次に、このオーロラ爆発開始位置付近の、Kevo 観測所（磁気緯度 66.2 度、フィンランド）取得のオーロラ全天画像を調べた。全天画像では、1941:00 UT にオーロラ爆発が開始し、遅くとも 1941:40 UT では PEX は進行中であった。一方、Geotail 衛星が観測した AKR は 1941:20 UT 頃に高周波 AKR が発達し、1942:40 UT に低周波 AKR が発達した。

これらの観測を比較すると、PEX 開始は、高周波 AKR 開始時に対応しており、低周波 AKR 開始時に対応せず、その 1 分以上前であった。また、低周波 AKR が生じた時刻には、地上全天画像では、別の強いオーロラが発生していたが、このオーロラは極側境界よりも赤道側に位置し、極側ではなく赤道側に移動した。以上の結果により、低周波 AKR 開始は、必ずしも PEX 開始には対応せず、本質的には強いオーロラの発生に対応すると考えられる。

オーロラ爆発と磁気再結合の地上全天及び磁気圏尾部における同時観測

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Simultaneous all-sky and multi-satellite observations of auroral breakup and magnetic reconnection

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A substorm is a large-scale disturbance including auroral breakup in the ionosphere and magnetic reconnection in the magnetotail. Two predominant models of the substorm time history have been proposed: the near-Earth neutral line (NENL) model and the current disruption model. The former is of outside-in type with tailward propagation of the disturbance, whereas the latter is of inside-out type with earthward propagation of the disturbance. To determine such time histories of such substorms using aurora all-sky and magnetotail multi-satellite observations, the National Aeronautics and Space Administration (NASA) is conducting a mission named the ”Time History of Events and Macroscale Interactions during Substorms (THEMIS)”.

The time history of a substorm is expected to be best clarified when satellites are aligned along the tail axis. A substorm occurred under such a satellite distribution on 0743:42 UT February 27, 2009, and we investigated the auroral breakup and fast plasma flows produced by the magnetic reconnection in this substorm. The THEMIS satellites observed that a northward magnetic field variation propagated earthward. Because this earthward propagation is consistent with the NENL model, observation of a substorm onset after the magnetic reconnection was expected. However, the substorm onset was observed in the all-sky images before the magnetic reconnection, as noted in a previous study.

In this study, we report that another earthward fast plasma flow occurred before the substorm onset, indicating that another magnetic reconnection occurred before the substorm onset. In addition, we confirm that the above mentioned post-onset magnetic reconnection occurred simultaneously with auroral poleward expansion, within a 1-min period. These results support the NENL model and further suggest that the two-step development of magnetic reconnection is a key component of the substorm time history.

サブストームは、電離圏におけるオーロラ爆発や磁気圏における磁気再結合を含む大規模な擾乱現象である。このサブストームの時間発展を説明する仮説として、オーロラ爆発 (サブストームオンセット) が先行する電流消失モデル、磁気再結合が先行する近地球磁気中性線 (near-Earth neutral line, NENL) モデルが提唱されている。前者は擾乱が地球から磁気圏尾部方向に伝播する inside-out 型、後者は擾乱が磁気圏尾部から地球方向に伝播する outside-in 型である。このようなサブストームの時間発展を明らかにするために、地上全天オーロラ観測と複数衛星による磁気圏尾部観測を用いた、NASA による Time History of Events and Macroscale Interactions during Substorms (THEMIS) 計画が実施されている。

サブストームの時間発展を調べるためには、複数衛星が尾部方向に一列に並んでいる配置が最適である。今回は、そのような衛星の配置の下で 2009 年 2 月 27 日 0743 UT に開始したサブストームについて、Gillam(磁気緯度 66.0 度) で観測されたオーロラ爆発と、THEMIS 複数衛星で観測された磁気再結合に伴う尾部プラズマ高速流の解析を行った。このイベントでは、磁気再結合により生じた北向き磁場変動が地球向きに伝播していたことが複数衛星観測から推定される。この地球向きの伝播は NENL モデルに沿うため、サブストームの開始は磁気再結合よりも後であることが期待される。しかし、地上全天観測により同定したサブストーム開始は、磁気再結合よりも前であることが先行研究で指摘されていた。

本研究では、このサブストーム開始前に地球向きプラズマ高速流、すなわち磁気再結合が生じていたことを新たに発見した。また、先述したサブストーム開始後の磁気再結合は、オーロラの poleward expansion の開始と 1 分以内で同時であることを確認した。これらの結果は、NENL モデルを支持し、さらに磁気再結合が二段階発達することがサブストームの時間発展の鍵となっていることを示唆する。

オーロラ全天画像とPi2地磁気脈動を用いたサブストームオンセットの解明

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Association between substorm onsets in auroral all-sky images and geomagnetic Pi2 pulsations

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Substorms are explosive disturbances in the magnetosphere and ionosphere of Earth. Substorm onsets are often identified using sudden auroral brightenings (auroral breakup) or geomagnetic Pi2 pulsations. These auroral brightenings and Pi2 pulsations are supposed to occur simultaneously within approximately 1 min of each other. However, as auroral brightenings typically include a two-stage development, this simultaneity is not straightforward.

In this study, we clarify the correspondence between Pi2 pulsations and auroral brightenings, including the two-stage development. The first stage of the development is the sudden brightening of an auroral arc near the midnight (initial brightening) and the second stage is the poleward expansion of the auroral arc. We compared all-sky images (3 s resolution) in Canada and geomagnetic observations (0.5-1 s resolution) in North and Central America, using data from the THEMIS project. In this study, we examined three substorms events that exhibit evidence of the two-stage auroral development.

In the first event (4 March 2008), an auroral initial brightening occurred at 0533:57 UT and a poleward expansion was observed at 0538:12 UT (4 min after the initial brightening) in Gillam (magnetic latitude:66.0 ° , longitude:333 ° , MLT:22.9). In contract, the Pi2 pulsation started at 0539:30 UT, which is closer to the time of the poleward expansion, in Carson City (magnetic latitude:45.0 ° , longitude:304 °). and San Juan (magnetic latitude:27.9 ° , longitude:6.53 °). Thus, we consider this Pi2 pulsation as corresponding to the poleward expansion rather than the initial brightening. This correspondence was also seen in the other two events, suggesting that it is not exceptional. We interpret that the Pi2 pulsation corresponds to the poleward expansion because both are caused by the magnetic field dipolarization, which is a drastic change that propagates from low- to high-latitude field lines.

サブストームは、地球磁気圏と電離圏における爆発的な電磁擾乱である。サブストームの開始は、オーロラの突然の増光（オーロラ爆発）やPi2地磁気脈動などにより同定される。このオーロラの増光とPi2脈動は、約1分以内で同時であると想定されている。しかし、オーロラの増光が典型的には2段階に発達することに着目すると、この同時性は自明ではない。1段階目の発達は、真夜中付近で起こるオーロラアークの突然の増光（initial brightening）、2段階目は、アークが極方向に拡大する poleward expansion である。本研究では、この2段階発達が顕著である3例のサブストームを調べた。用いたデータは、THEMIS計画で取得されている、カナダのオーロラ全天画像（3秒値）と北中米の地磁気観測（0.5-1秒値）である。

最初の例（2008年3月4日）では、initial brightening が0533:57 UTに、poleward expansion が4分後の0538:12 UTに、Gillam（磁気緯度：66.0度、磁気経度：333度、MLT：22.9時）で観測された。一方、Pi2脈動は0539:30 UTにCarson City（磁気緯度：45.0度、磁気経度：304度）とSan Juan（磁気緯度：27.9度、磁気経度：6度）で開始したため、poleward expansionに対応すると考えられる。この対応関係は他の2例においても、以下の様に同様であった。2例目（2008年2月29日）では、initial brightening が0433:30 UT、poleward expansion が6分後の0439:18 UTに、Fort Smith（磁気緯度：67.3度、磁気経度：307度、MLT：20.2時）で観測された。一方、Pi2脈動は、0438:40 UT（initial brightening から5分後）にCarson Cityで開始していた。最後に3例目（同日）は、initial brightening が0818:36 UTで、poleward expansion が2分後の0820:24 UTに、Athabasca（磁気緯度：61.9、磁気経度：307度、MLT：23.8時）で観測された。一方、Pi2脈動は、0821:00 UT（initial brightening から2分後）にSan Juanで開始していた。

以上の3例から、Pi2脈動は、initial brightening ではなく、オーロラの2段階目の発達である poleward expansion に対応していることが示唆される。一般に、Pi2脈動は、地球の磁力線が衝撃を受けることにより生じると考えられる。一方、オーロラの poleward expansion は、磁気赤道面において内側から外側の磁力線に擾乱が伝播していることの投影であると考えられる。従って、Pi2脈動と poleward expansion の対応は、磁気圏において引き伸ばされた磁力線が急激に元に戻る、磁気双極子化に起因した、間接的関係であると考えられる。

THEMISデータによるサブストームと疑似サブストームに伴う磁気圏尾部変動の統計解析

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A statistical study of near-Earth magnetotail evolution duing substorms and pseudosubstorms with THEMIS data

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Substorms and pseudosubstorms (pseudobreakups) are very similar phenomena. In terms of auroral morphology, pseudosubstorms are generally more localized and more short-lived, compared with substorms, and are not accompanied by poleward expansion. We examined auroral development for events from November 2007 through April 2010, using data from THEMIS all-sky imagers. We defined events accompanied and not accompanied by poleward expansion as substorms and pseudosubstorms, respectively. To understand the cause of auroral development, we investigated temporal and spatial development of the near-Earth magnetotail during substorms and pseudosubstorms, based on superposed epoch analysis of THEMIS data. We find that Vx begins to increase at -9.5 >X(GSM)>-11.5 Re around onset for both substorms and pseudosubstorms. This seems to be due to earthward flows caused by magnetic reconnection. The northward Bz also increases around onset at -9.5 >X>-10.5 Re both substorms and pseudosubstorms. The amount and rate of Bz change are larger for substorms than for pseudosubstorms. In the earthward (-7.5 >X>-9.5 Re) and tailward (-10.5 >X>-12.5 Re) regions, Bz increases substantially for substorms, whereas it does not increase very much for pseudosubstorms. These results indicate that dipolarization is weaker for pseudosubstorms than for substorms, and the dipolarization region does not spread extensively for pseudosubstorms. We, therefore, suggest that current disruption related to dipolarization does not develop tailward and hence auroral poleward expansion does not occur for pseudosubstorms. Meanwhile, the plasma and magnetic pressures increase at -6.5 >X>-7.5 Re after onset in association with dipolarization, particularly for substorms. The total pressure (the sum of the plasma and magnetic pressures) prior to the onset is larger in that region for substorms than for pseudosubstorms. At -7.5 >X>-8.5 Re the total pressure hardly differ between substorms and pseudosubstorms. Thus we conclude that the spatial gradient of the total pressure is a key that determines whether the current disruption takes place, that is, whether initial activation develops into a substorm or into a subsiding pseudosubstorm.

サブストームと疑似サブストーム (疑似ブレイクアップ) はともによく似た現象である。オーロラの発生という観点において、一般に後者は前者と比べ小規模で継続時間が短く、極方向の拡大 (Poleward Expansion) がないものを指す。本研究では 2007 年 11 月から 2010 年 4 月までのイベントについて、THEMIS の全天カメラのデータから極方向の拡大の有無を調べ、極方向の拡大が見られたものをサブストーム、見られなかったものを疑似サブストームとした。サブストームと疑似サブストームの発達の違いの要因の手掛かりを得るため、それぞれについて THEMIS 衛星データを用いて、オンセット前後の磁気圏尾部プラズマシートにおけるプラズマ速度、磁場、圧力の時間変化を時間重畳法 (Superposed Epoch Analysis) により調べた。その結果、-9.5 >X(GSM)>-11.5 Re の領域では、サブストーム、疑似サブストームともにオンセット付近で Vx の増大がみられた。これは磁気リコネクションに伴う地球向きプラズマ高速流であると考えられる。また同様に-9.5 >X>-10.5 Re の領域ではサブストーム、疑似サブストームともにオンセット付近で Bz の増大がみられ、サブストームの方が変化量と変化率が大きかった。それよりも地球側 (-7.5 >X>-9.5 Re) と尾部側 (-10.5 >X>-12.5 Re) の領域では、疑似サブストームでは Bz はあまり変化しなかった。このことから、疑似ブレイクアップではサブストームに比べ磁気双極子化の度合いが弱く、また広範囲で起こらないことが示唆される。つまり、磁気双極子化に伴う Current Disruption が尾部方向に発展せず、オーロラの極方向の拡大が発生しないと考えられる。一方、圧力について、-6.5 >X>-7.5 Re の領域では、プラズマ圧と磁気圧がともにオンセット後に磁気双極子化に伴って増大し、特にサブストームの場合にその傾向が著しかった。また、サブストームの場合は、オンセット数分前の磁気圧とプラズマ圧の和 (全圧) が疑似ブレイクアップの場合に比べて大きかった。-7.5 >X>-8.5 Re においてサブストームと疑似サブストームでほとんど全圧に差がないことを考え合わせると、-8 Re 付近での圧力の空間勾配の大きさが Current Disruption 領域が尾部方向に広がる要因、すなわちサブストームに発展するか、疑似サブストームに留まるかを決定する要因であることが結論付けられる。

サブストーム統一モデルの構築に向けて

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Toward a unified model of substorm

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Numerous models of substorms have been proposed so far, and they are roughly divided into two categories, i.e., the outside-in category that is represented by the near-Earth neutral line (NENL) model and the inside-out category represented by the current disruption model or the ballooning instability model. Controversies have been raised for many years over the validity of those models. However, in recent years we have obtained important clues to solve this long-standing issue by analyzing THEMIS probe data for substorms and pseudo-substorms separately. [Fukui et al., 2017]

The key is the plasma pressure in the equatorial region, and it was about 1.3 times higher in substorms, than the pseudo-substorm in the region between X ~-7 and -8 Re. However, no difference was found beyond X ~-10 Re. Therefore, the spatial gradient of the plasma pressure in the region of X ~-7.5 Re must be a necessary condition for the occurrence of substorm. Abrupt earthward flows originated from the catapult current sheet relaxation and subsequent magnetic reconnection at the NENL just prior to the onset is a common signature for both substorm and pseudo-substorm, which seems to be essentially a result of the tearing instability in the magnetotail. [Uchino and Machida, 2015] The subsequent earthward flows must initiate some instability, quite likely the ballooning instability around the flow braking region.

Substorms do not occur only with the magnetic reconnection. If there is enough plasma pressure gradient, the system can develop into a substorm. Otherwise, it will end up with a pseudo-substorm. We emphasize that both NENL model and the ballooning instability model are partially correct but incomplete, and the true model of substorm can be constructed by synthesizing multiple models of substorm including at least these two models.

これまでに数多くのサブストームモデルが提案されているが、それらの大部分のものは、NENL（Near-Earth Neutral Line）モデルで代表される Outside-In モデルと、電流遮断モデルまたはバルーニング不安定モデルで代表される Inside-Out モデルに分類される。そして、それらのモデルの妥当性を巡って長年論争が繰り広げられてきた。しかし、近年、THEMIS 衛星で取得されたデータをサブストームと疑似サブストームについて別々に解析することで、この難問を解決するための重要な手掛かりが得られた。 [Fukui et al., 2017]

その鍵となるのは、赤道領域のプラズマ圧の空間勾配である。X ~-7 Re と-8 Re の間のサブストーム時のその値は、疑似サブストーム時に比べて約 1.3 倍大きい。しかし、X ~-10Re 以遠では殆ど差がみられない。したがって、X ~-7.5 Re の領域のプラズマ圧の空間勾配の大きいことが、サブストームが発生するための必要条件であることが推定される。サブストーム開始直前のカタパルト電流シートの緩和およびその後の磁気リコネクションを原因とする地球向きのプラズマ流は、本質的に磁気圏尾部におけるティアリング不安定の結果であると考えられる。[Uchino and Machida, 2015] その流れの発生は、サブストームと疑似サブストームに共通した特徴であるが、サブストームにおいては、それが何らかの不安定性、恐らく、バルーニング不安定を引き起こすものと推定される。

ここで重要なことは、サブストームは、磁気リコネクションのみでは発生しないという事実である。サブストームは、十分なプラズマ圧力勾配がある場合にのみ発生し、それ以外の場合は、単に疑似サブストームに止まってしまう。NENL モデルとバルーニング不安定モデルはそれぞれ部分的に正しいが完全でない。真のサブストームモデルは、少なくとも、この２つを含む複数のサブストームモデルを統一的に組み合わせることによってはじめて構築できる。

南極昭和基地における近赤外波長領域（1.0-1.6 microns）オーロラへの広帯域/高波長分解能・分光観測計画

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A ground-based observation plan for aurora spectrum in near infrared wavelength (1.0-1.6 microns) at Syowa Station

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The motivation of this study is further understanding of dayside magnetosphere and terrestrial atmosphere coupling system by using continuous observation with high temporal and spatial resolutions. Dayside aurora, polar patch, and airglow should be key phenomena for the understanding. In particular, those phenomena in near infrared (NIR) wavelength are crucially important because lower background sky luminosity by Rayleigh scattering may allow us to conduct ground-based optical observation even in dayside. Continuous dayside optical monitoring in aurora region and cusp give us a clue to understanding of substorm pre-onset sequences at cusp region, magnetopause dynamics related to solar wind shocks, and wave-particle interactions due to electromagnetic ion cyclotron waves and whistler mode chorus. However, NIR aurora has a total lack of its spectral information with enough resolution to make a feasibility study in comparison to that in visible wavelength.

We are now planning ground-based spectroscopic observation in NIR wavelength ranging from 1.0 to 1.6 microns, which covers auroral emissions in N_2 1st Positive (1.2 microns) and N_2^+ Meinel (1.1 and 1.5 microns) [*Jones* 1974; *Zhou et al*., 2007]. This observation will start at Syowa Station (69.0^{o}S, 39.6^{o}E) in Antarctica from March 2018 when austral summer ends. We designed a narrow field spectrometer with medium-high spectral resolution that mainly consists of Czerny-Turner type imaging spectrometer (HORIBA, iHR320) with one entry port and two exit ports. This spectrometer has two mirrors and three diffractive gratings in a rotating turret. A toroidal mirror for collimating corrects for astigmatism so that the tangential (resolution optimized) and sagittal (imaging optimized) focal planes cross at the center of the focal plane. Another larger focus mirror allows the entire flat field to be used without vignetting. Collecting optics, equipped outside the spectrometer, are a gold coated off-axis parabolic mirror and a NIR longpass filter for removal of secondary diffracted light in visible wavelength. Two detectors for two exit ports are NIR-photomultiplier tube (PMT) module with thermoelectric (TE) cooling system (Hamamatsu, H10330C-75) and InGaAs camera with 640 x 512 pixels and TE cooling in 4 stages (Photon etc., ZephIR 1.7). NIR-PMT module in combination with an exit slit measures precisely individual emission spectrum with high resolution of 0.006 nm. On the other hand, InGaAs camera covers wider spectral ranges (200 nm, 45 nm, 25 nm) and medium spectral resolutions (0.31 nm, 0.070 nm, 0.038 nm) depending on the three gratings (150 gr/mm, 600 gr/mm, 900 gr/mm). The two detectors cannot be operated simultaneously but can be easily switched by a software. Additionally, Argon lamp is used as calibration source for measured wavelength in a range from 1.0 to 1.6 microns.

In this presentation, we are going to report a final configuration of the spectrometer and a current status of this project. Results of test observations at Tachikawa (35.7^{o}N, 139.4^{o}E), including a first light of OH airglow emissions around 1.5 microns, will be also demonstrated and subsequently discussed the specification of the spectrometer in detail.

MMS衛星観測データを用いた外部磁気圏Pc5波動内におけるプロトンからEMIC波動へのエネルギー輸送の直接計測

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Direct measurements of energy transfer from hot protons to EMIC waves observed by MMS during Pc5 waves in the outer magnetosphere

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Wave-particle interactions have been suggested to play a crucial role in energy transfer in collisionless space plasmas in which the motion of charged particles is controlled by electromagnetic fields. We report the temporal variation of energy transfer from hot anisotropic protons to electromagnetic ion cyclotron (EMIC) waves during a compressional ULF wave event using the data obtained by the four MMS (Magnetospheric Multiscale) spacecraft traversing the duskside outer magnetosphere. For the ULF wave, the period was about 2-5 minutes (Pc5 frequency range), and the magnetic and ion pressures were in antiphase, such that the total pressure remained almost constant. They were likely mirror mode type structures. The burst ion data from Fast Plasma Investigation Dual Ion Spectrometer (FPI-DIS) with a time resolution of 150 ms are available for two of the EMIC wave events during the ULF wave. Electric field data from the double probes were not usable to analyze the wave electric field due to the fluctuation with a frequency of ˜0.1 Hz likely caused by ion beams from Active Spacecraft Potential Control (ASPOC) neutralizers. However, perpendicular electric fields were estimated using the cross product of the cold ion velocity and the magnetic field. To directly detect energy transfer from hot protons to EMIC waves, we apply the Wave-Particle Interaction Analyzer (WPIA) method [*Fukuhara et al.*, 2009; *Katoh et al.*, 2013] to the data. The energy transfer rate by cyclotron resonance was calculated as the wave component of the perpendicular electric fields and ion current perpendicular to the magnetic field around the resonance velocity which is called the resonant current. The energy transfer rate peaked at the local minima of magnetic field intensity, which corresponds to the maxima of the ion pressure in the compressional ULF wave. This result indicates that the spontaneous EMIC wave generation is affected by ULF waves, and preferential locations for the cyclotron resonant energy transfer are magnetic field intensity dips. In these dips, both of the relatively low resonance velocity due to small magnetic field intensity and the enhanced hot proton flux can contribute to the enhanced energy transfer from hot protons to the EMIC waves by cyclotron resonance.

磁気圏におけるイオン温度空間分布の質量依存性

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Mass dependence of ion temperature spatial distributions in the magnetosphere

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Heating and acceleration of magnetospheric plasma have been studied using in-situ plasma and field observations. However, dominant heating/acceleration mechanisms and areas are not well understood. Moreover, it remains unclear whether the heating/acceleration mechanism depends on mass. It is thus necessary to investigate ion velocity distributions for several major species in a wide energy range including typical ion energies in the magnetosphere. However, there were a few satellite missions that can observe the thermal component of magnetospheric plasma with mass determination. There have been therefore a small number of studies that focus on mass-dependent processes in the typical energy range (<1-10 keV) of magnetospheric ions.

In this paper, we investigate heating and acceleration mechanisms of magnetospheric ions by comparing spatial variations of H+, He+, and O+. We use the data obtained by the HPCA instrument on board the MMS satellite which is in a low-inclination elliptical orbit with an apogee of about 12 Re and a perigee of about 1000km. The HPCA instrument can measure H+, He+, and O+ in a few eV to 40 keV energy range with a time resolution of about 10 seconds. Using 20-min averaged data for the period of September 2015 to September 2016, we examined density and temperature spatial distributions. First, we divided an equatorial plane into 0.5 Re × 0.5 Re bins and then calculated median of density and temperature in each bin. Next, we focused on around noon and midnight where the satellite stayed near the magnetic equator.

The results show that the temperature of He+ increased in the near-Earth regions (r smaller than 9Re) compared to H+ and O+ in both daytime and nighttime. We found a difference in temperature radial gradient between ion species at r smaller than 9 Re, and the gradient was smaller for any ions beyond 9 Re. On the night side, the parallel component of the temperature to the background magnetic field (T//) shows mass dependence larger than the perpendicular component (Tperp). On the other hand, no difference between the components is seen on the day side. These results suggest that the dominant acceleration/heating mechanism is different between He+ and O+, or there is a phenomenon that selectively heats only He+. We will also investigate differences/similarities in behavior between hot plasma and cold plasma. In addition, we will analyze velocity distribution function data for typical events of stronger temperature radial gradient of He+ than H+ and O+.

現在まで、様々な人工衛星の「その場」観測によって、磁気圏プラズマの加熱・加速研究が行われてきた。しかし支配的な加速メカニズムや加速領域は未だよく理解されていない。また加熱・加速機構が質量によって異なっているのか未解明である。加熱・加速プロセスを質量依存も含めて明らかにするためには、低いエネルギー帯の組成も含めた広範囲のエネルギー帯の描像を確立する必要がある。しかし磁気圏の広範囲にわたる地球磁気圏プラズマの熱的成分のイオン種別解析は、観測が困難であったため、磁気圏イオン（特に外部磁気圏）の典型的なエネルギー帯（＜1-10 keV) の粒子種依存過程に着目した研究は少ない。本研究では起源が異なる O+と H+の比較に加え、同じ地球起源である O+と He+を比較することで磁気圏イオンの加熱・加速メカニズムを調査する。

本研究では近地点 1000km から遠地点 12Re の範囲を周回する MMS 衛星に搭載された HPCA により得られたデータを利用する。HPCA は数 ev-40keV の H+、He+、He+、O+を約 10 秒の時間分解能で観測している。我々は、2015 年 9 月 1 日から 2016 年 9 月 1 日までのデータを用いて、磁気圏の H+、He+、O ＋の密度、温度の空間分布を調査した。具体的には、磁気赤道面付近の 6 Re-12Re の領域を 0.5Re × 0.5Re の bin に区切り、各 bin の密度、温度の中央値を示した空間分布図を作成した。また磁気赤道付近に長く滞在する正午付近、真夜中付近に分け、それぞれの場合の密度、温度の 20 分平均値を 0.5Re 毎にプロットした。

以上の解析から昼側、夜側いずれの場合についても He+の温度が、O+や H+と比べて、地球に近づくにつれて大きく上昇していることが示された。しかし、イオン種毎の温度勾配に差があるのは 9 Re より地球側であり、9 Re 以遠はいずれのイオンについても勾配が小さくなっている。また夜側での温度の背景磁場に平行な成分（T//）は垂直成分（Tperp）と比べて粒子依存性が大きかった。一方、昼側では、温度成分のイオン種依存性の差異は見られなかった。これらの結果は、太陽風起源である H+だけでなく同じ地球起源の He+と O+であっても支配的な加速・加熱機構が異なっていること、もしくは He ＋のみを選択的に加熱する現象が存在することを示唆している。今後は熱いプラズマと冷たいプラズマに分けてそれぞれの振る舞いの違いについて調査する。また今回得られた傾向が顕著なイベントについてより詳細な解析を行っていく。

MMS搭載FPIによるプラズマシート・ローブ境界の高時間分解能観測

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High time resolution plasma sheet - lobe boundary observation by FPI on MMS

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Plasma sheet - lobe boundary (PSBL) in the Earth's magnetotail is a special region that is surrounded by plasma sheet with hot plasma and lobe with cold plasma. Velocity dispersed ion and electron beams are the characteristic signature of the low energy particles in the PSBL. Three components of ions such as lobe cold ions, earthward flowing and tailward flowing velocity dispersed ions are often observed at PSBL in the near-Earth magnetotail. Geotail observations revealed that the plasma sheet - lobe boundaries between near-tail to far-tail region can be identified as slow mode shocks that contribute to the heating of the lobe cold ions in addition to the heating in the region near magnetic reconnection line. Although the ion heating process at the slow-shock plasma sheet - lobe boundaries were also investigated using Geotail low energy particle data obtained by LEP-EAi and EAe, it is still unclear due to the low time resolution ion measurements. The cold ions were heated nearly within one sampling time (12 seconds) of LEP-EAi. Since MMS was launched on 12 March 2015, MMS has been continuing to produce highest quality data ever we had. MMS mainly observed dayside magnetic reconnection region for two years after the launch. After May 2017, MMS started observation of the night side reconnection region. The same group that developed the low energy particle experiment (LEP) on Geotail has been participating to the development of one of the instruments on MMS that is FPI-DIS (Fast Plasma Investigation - Dual Ion Sensor). Design, fabrication, assembly, and the initial tests of the 16 Flight Model DIS sensors were made in Japan collaborating with U.S. and French colleagues. One FPI-DIS sensor is composed of two Top-Hat type electrostatic analyzers looking at two directions (45 degrees apart) and controlling electronics common to the two analyzers. There also exist FOV (Field Of View) scanning deflectors at the entrance of the analyzers. The time resolution to obtain 3D distribution function of DIS is 4.5 sec for the fast survey mode, and 150 msec for the burst mode. The electron sensors FPI-DES (Dual Electron Sensor) that is simultaneously operated with DIS has much higher timer resolution of 30 msec for the burst mode. We will search for the slow-shock plasma sheet - lobe boundaries by using electron and ion data obtained by FPI-DIS and FPI-DES, and magnetic field data. We will report the variation of the ion distribution function accompanying ion heating at the slow-shock plasma sheet - lobe boundaries.

地球磁気圏尾部のプラズマシート・ローブ境界は、ローブの冷たいプラズマと、プラズマシートの暖かいプラズマの間に挟まれた領域であり、速度分散を持ったイオンや電子のビームが存在するなど、特徴的な領域である。特に、地球に近い領域になると、地球から磁気圏尾部へ流れながらローブからプラズマシートへ向かうローブの冷たいイオンと、磁気圏尾部から飛来するイオンビーム、そしてそれが地球近傍で磁気ミラー反射されて磁気圏尾部へ戻るイオンビームなどの複数の成分が同時に観測される複雑な領域であるとも言える。Geotail衛星の観測によって、磁気圏近尾部の領域から遠尾部の領域にかけてのプラズマシート・ローブ境界は、ある割合で、スローショックとなっていることが明らかとなり、磁気圏尾部の磁気リコネクション領域の近傍に加えて、プラズマシート・ローブ境界もローブの冷たいプラズマを加熱する役割を担っていることがわかっている。このプラズマシート・ローブ境界においてローブの冷たいイオンが、プラズマシートに侵入するまでの加熱過程については、Geotail衛星に搭載された低エネルギー粒子計測装置LEPによって観測されたデータを用いて研究がなされた。しかしながら、スローショック境界におけるイオンの加熱は磁気圏尾部の衛星に対する速度にも依るが、Geotail衛星に搭載された低エネルギーイオンの観測装置の時間分解能である12秒では殆ど1サンプルの間にイオンは加熱されてしまうため、その構造については未解決のままであった。

MMS衛星は、4機の衛星で構成される編隊飛行衛星で、2015年3月12日に打ち上げられ、打ち上げ後2年の間地球磁気圏の昼間側の磁気リコネクション領域の観測を重点的に行った後、2017年5月以降は、磁気圏尾部の磁気リコネクション領域の観測を進めている。本MMS衛星には日本のグループもMMS衛星搭載FPI(Fast Plasma Instrument)を構成するセンサーであり、低エネルギーイオンのエネルギースペクトルを測定するDIS(Dual Ion Sensor)の設計・製作・アセンブル・単体環境試験・初期性能確認試験を担当して深くMMS計画に参加している。MMSは同一構成の4機の編隊飛行衛星から成るが、1機の衛星当たり4台のDISが搭載されており、計16台のDISが観測を継続している。

DISは、2台のTop-Hat型静電分析器と呼ばれる荷電粒子のエネルギー分析器を45度離して共通の電子回路部と共に搭載したもので、視野を電気的に偏向するための電極を入射口に備えている。DISは、2015年3月12日の打ち上げ以降、計16台のフライトモデル全てがほぼ正常に動作している。DISの時間分解能はモードによっても異なるが、FASTサーベイと呼ばれるモードで、4.5秒、バーストモードと呼ばれるモードでは150ミリ秒で低エネルギーイオンの3次元分布関数を取得することができる。DISと同時に電子の計測を行っているDES(Dual Electron Sensor)はDISより更に高い時間分解能である30ミリ秒で電子の3次元分布関数を取得することができる。本研究では、DISとDESのデータと磁力計によって得られた磁場のデータを用いて、スローショックとなっているプラズマシート・ローブ境界を探し、その境界におけるイオンの加熱に伴う分布関数の変化について調べた結果を報告する。

Investigation of the magnetic neutral line region with the frame of two-fluid equations

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Magnetic reconnection is a basic physical process by which energy of magnetic field is converted into the kinetic energy of plasmas. In recent years, MMS mission consisting of four spacecraft has been conducted aiming at elucidating the physical mechanism of merging the magnetic fields in the vicinity of the magnetic neutral line that exists in the central part of the structure. In this paper, we examine the magnetic field frozen in relation near the magnetic neutral line as well as the causal relationship between electron and ion dynamics in the frame of two fluid equations. It is thought that the electron dissipation region with the thickness of about the electron inertial length surrounds the magnetic neutral line, and the ion dissipation region with the thickness of about the ion inertia length further surrounds them. Theoretically, it is shown that electrons are frozen-in to the magnetic fields while ion-frozen-in relation is broken in the ion dissipation region. However, when we examined the observational data around 1307 UT on October 16, 2015 when MMS spacecraft passed through the vicinity of the magnetic neutral line [Burch et al., Science 2016] , it was confirmed that the frozen-in relation was not established for electrons in the ion dissipation region. In addition, we found that intense wave electric field activities in this region. From the spectral analysis of the waves, it turned out that their characteristic frequencies are the lower-hybrid and electron cyclotron frequencies.In the framework of the two-fluid equation, we can evaluate the values of each term of the equations of motion for both ions and electrons except for the collision term from MMS spacecraft data. Therefore, it is possible to obtain collision terms for both species. Since magnetospheric plasma is basically collisionless, it is considered that the collision term is due to anomalous resistivity associated with the excited waves . On the other hand, in the usual two-fluid equation system, the two vectors corresponding to the collision terms of ions and electrons have the same absolute value. Because the force exerted between the two is the internal force, they should face exactly in the opposite direction. However, the vectors corresponding to the collision terms obtained by using the actual data did not satisfy such a condition. In the previous presentation (JpGU, 2017), we reported that the momentum carried by the waves cannot be neglected, and also some instrumental error for measuring physical parameters may cause such a discrepancy. Moreover, the frequency of the low-hybrid wave is about 10 Hz, so that its period is100 ms which is almost the same to the sampling time of 150 ms for the ion measurement. Therefore, the time average is not sufficient to evaluate the collision term correctly, and it is natural that term does not cancel out with the electron collision term.After careful examination, we conclude that the effect of the anomalous resistivity in the ion dissipation region acts to some degree that cannot be ignored in the equation of motion of the two-fluid system.

A statistical study of slow-mode shocks observed by MMS in the dayside magnetopause

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Petschek's reconnection theory [1964] provides a means for faster reconnection by creating X-line geometry with two pairs of slow-mode shocks. Earth's magnetosphere acts as a natural laboratory to investigate the presence and role of these slow-mode shocks. Considerable amount of studies have reported the presence of the slow-mode shocks in the magnetotail [e.g. Feldman et al., 1987; Saito et al., 1995; Eriksson et al., 2004] but only a few have reported the slow-shocks in the magnetopause [Walthour et al., 1994; Sonnerup et al., 2016]. The slow-shocks are observed in the magnetosheath side and/or magnetosphere side of the magnetopause. These studies suggest that strong pressure anisotropy and presence of cold ions could play an important role in determining the structure of the slow-mode shocks in the magnetopause. These studies also report the presence of rotational discontinuity and theoretical studies have also indicated that the magnetopause consists of multiple MHD discontinuities [e.g., Hau and Wang, 2016]. The solar wind conditions as well as the local conditions in the magnetosphere can affect the structure of the magnetopause. One of the reasons of the small number of the slow-shock events reported for the magnetopause is the lack of the high time resolution data to separate multiple discontinuities before MMS. Thus, an exhaustive study with many events is needed to understand the underlying physics of the slow-shocks in the magnetopause.

Here we present a statistical study of slow-mode shocks in the dayside magnetopause crossings observed by MMS (Magnetospheric Multiscale). For this study, we used the data from FGM and FPI instruments onboard the MMS satellites. Fast survey data were analyzed from 1^{st} Sept, 2015 to 31^{st} Jan, 2017. For event selection, we checked the southward IMF magnetopause crossings with jet ($|V_{gsm}|$is greater than equal to 200 km/s). We ensured the presence of the magnetosheath side in our events by using Plasma Beta greater than 1 and M_A less than 1 conditions. The events obtained by using this criterion were then checked by using burst mode data and incomplete magnetopause crossings were removed to get a set of 71 full crossings from the magnetosheath to the magnetosphere. Ranking-Hugoniot analysis was applied on these crossings after determining two separate deHoffmann-Teller frames for each side. Out of these 71 crossings, 23 magnetopause crossings were identified as the slow-mode shocks. Among the 23 events, 13 events contained slow-shock on the magnetosheath side whereas 10 contained slow-shock on magnetosphere side. We will report on the relation of these slow-mode shocks with solar wind conditions and the local parameters as well as on their relative location to other discontinuities in the magnetopause.

低高度衛星の磁場観測データを用いた磁気圏プラズマ空間構造の推定

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The spatial structure of magnetospheric plasma disturbance estimated by using magnetic data obtained by LEO satellites.

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Field-aligned currents with various spatial scales flow into and out from high-latitude ionosphere. The magnetic fluctuations observed by LEO satellites along their orbits having period longer than a few seconds can be regarded as the manifestations of spatial structure of field aligned currents.This has been confirmed by using the initial orbital characteristics of 3 SWARM-satellites. From spectral analysis, we evaluated the spectral indices of these magnetic fluctuations and investigated their dependence on regions, such as magnetic latitude and MLT and so on. We found that the spectral indices take quite different values between the regions lower than the equatorward boundary of the auroral oval (around 63 degrees' in magnetic latitude) and the regions higher than that. On the other hands, we could not find the clear MLT dependence. In general, the FACs are believed to be generated in the magnetiospheric plasma sheet and boundary layer, and they flow along the field lines conserving their currents.The theory of FAC generation [e.g., Hasegawa and Sato ,1978] indicates that the FACs are strongly connected with magnetospheric plasma disturbances. Although the spectral indices above are these of spatial structures of the FACs over the ionosphere, by using the theoretical equation of FAC generation, we evaluate the spectral indices of magnetospheric plasma disturbance in FAC's generation regions. Furthermore, by projecting the area of fluctuations on the equatorial plane of magnetosphere (i.e. plasma sheet), we can estimate the spatial structure of magnetospheric plasma disturbance.

In this presentation, we focus on the characteristics of disturbance in midnight region and discuss the relations to the substorm.

高緯度電離層には様々なスケールの電流が存在する。特に、低高度衛星によって観測される軌道に沿った数秒より長周期の磁場変動は沿磁力線電流の空間構造を反映しており、このことは3機の低高度衛星からなるSWARM衛星の初期軌道特性を用いて確認されている。

スペクトル解析より、我々はこれらの磁場変動のスペクトル指数を評価し、その値の領域(磁気緯度やMLT)依存性を調べた。スペクトル指数はオーロラ帯の下限(磁気緯度約63度)を境に、高緯度側と低緯度側で顕著にとる値が変化したが、一方でMLTに関する明確な依存性は見られなかった。

一般に沿磁力線電流は磁気圏プラズマシートや境界層で生成され、磁力線に沿って電流を保存しつつ電離層へと伝わる。さらに、(Hasegawa and Sato ,1978)で示された沿磁力線電流生成の理論式より、沿磁力線電流と磁気圏プラズマの運動や構造とが強く結びついていることが示されている。

上記のスペクトル指数は、電離層での沿磁力線電流の空間構造についてのスペクトル指数であるが、沿磁力線電流生成の理論式を使うことで、沿磁力線電流生成領域における磁気圏プラズマのスペクトル指数を評価した。さらに、磁気圏モデルを用いて磁場変動をプラズマシートなど磁気圏赤道面に投影することにより、磁気圏プラズマの空間構造を議論する。

特に、本発表で真夜中領域に着目し、サブストームとの関連についても議論する。

リコネクションした磁力線に沿うカスプ電子降下の成長と減衰

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Growth and decay of cusp electron precipitation along the reconnected field lines

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Immediately after the open magnetic field line is created by reconnection, magnetosheath electrons and ions stream into the reconnected open flux tube. At low altitudes the injected ion energy flux tends to decrease with increasing distance from the origin of the open flux, and this feature is well understood. For the injected electrons, however, it is still not understood how the electron precipitation along the reconnected field lines changes with increasing distance from the origin of the open flux tube. In this study we examined the growth and decay of the electron precipitation along the reconnected open field lines by using observations of moving cusp auroras, which are thought to be caused by bursty and/or patchy reconnection, from an all-sky imager at Longyearbyen, Svalbard. We analyzed 630 nm aurora image data obtained at a time resolution of approximately 10 s. The results of the analysis show that the distance from the origin of the open flux is not an important parameter for the cusp electron precipitation along the reconnected field lines, and that to what extent the motion of the reconnected field lines is east-west aligned is important. We discuss this feature in terms of the intensification of associated field-aligned currents.

Strongly enhanced plasma lines observed by the EISCAT Svalbard Radar during the International Polar Year

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The plasma line (PL) is one of the signatures in the incoherent scatter radar spectrum and appears at frequencies up- and down-shifted from the transmitted signal by a few MHz. These frequency shifts respectively correspond to the frequencies of the down- and up-going scattering Langmuir waves plus the Doppler shift caused by the bulk motion of the electron gas. Although intensity of the PL is sometimes below noise level, it is occasionally enhanced and detectable in the presence of certain nonthermal features of the electron distribution function, such as local or magnetic conjugate photoelectrons and aurorally generated suprathermal (secondary) electrons. Especially during auroral activities, PL frequency and power may drastically change both with altitude and with time as reported from several case studies [e.g., Wickwar, 1978; Valladares et al., 1998; Kirkwood et al., 1995]. In companions paper [Ivchenko et al., submitted to Ann. Geophys.], data from the European Incoherent Scatter (EISCAT) Svalbard Radar (ESR) during the International Polar Year (IPY, from March 2007 to February 2008) are analyzed for statistical occurrence of enhanced PL. In this study, we use the same data set but focus on strongly enhanced plasma lines (sPL) with intensity higher than 0.1 K/Hz. Occurrence peak of sPL is found near 4 UT and 14 UT (~7 MLT and ~17 MLT), while occurrence frequency of enhanced PL becomes higher when photo-electrons caused by the Sun's EUV radiation are present. While occurrence frequency of enhanced PL is highest in summer (May-Jun) and lowest in winter (Nov-Jan), occurrence frequency of sPL is higher in spring (Feb-Apr) than in other seasons. Occurrence of sPL is mostly below about 180 km altitude, whereas enhanced PL appears over the measured altitude range up to 278 km. Occurrence of sPL shows clear Kp dependence through the year: higher occurrence frequency during higher Kp values. Both up- and down-shifted sPL were usually observed near both edges of the observed frequency range until November 2007 (~3.2 and 4.8 MHz; the latter should be aliasing) and near a center of the frequency range after December 2007 (~3.2 MHz). This frequency concentration may be attributed to 2-4 eV dip in the electron distribution function caused by excitation of vibration levels in N_2 [Nilsson et al, 1997], which results in low Landau damping and strong enhancement of Langmuir waves.

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大型短波レーダーや地上磁場で観測される磁気圏急圧縮に伴う電離圏対流変動

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Ionospheric electric field oscillations associated with Sudden Commencement seen by SuperDARN radars and ground magnetometers

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Sudden Commencement (SC) is observed mainly as a sudden increase of the H-component of geomagnetic field at low latitudes. Past studies showed that it is caused by a sudden compression of the magnetosphere associated with rapid increases of the solar wind dynamic pressure. At middle and high latitudes, SCs cause perturbations associated with twin vortex type ionospheric currents. It was reported that the disturbance of the ionospheric current and the electric field associated with SC consists typically of the Preliminary Impulse (PI) and the Main Impulse (MI). Previous studies reported that some of SC-associated electric field disturbances observed by SuperDARN radars show only the two successive pulses of PI and MI, while some others are accompanied by damped oscillations of the ionospheric electric field lasting for about several tens of minutes to an hour with periods of several minutes. The reason why both types of SC-associated disturbances can occur, however, have not yet been understood well. We examine the cause of the difference between the two kinds of SC events, using SuperDARN radars in the northern hemisphere covering ˜40 to 90 degree geomagnetic latitudes. For the analyzed period from January 2011 to December 2015, 244 SC events were identified and 61 events out of them were accompanied by the ionospheric electric field oscillations immediately following MIs, as observed by at least one SuperDARN radar.

We contrast 183 events (only PI and MI) with 61 events (oscillation following MIs) and find that the average of magnitude of dynamic pressure change does not seem to be the cause of the difference between the two types of disturbance associated with SC events. Regarding the magnetic local time (MLT) dependence of the ionospheric electric field oscillations, the occurrence rate is somewhat high from 15:00 MLT to 18:00 MLT. The seasonal variation of the occurrence rate tends to be lower in summer than in winter. We discuss the cause of the MLT dependence and the seasonal variation. In addition to the statistical study, we also made a detailed analysis of individual events. The result shows that some of them have global structures in the longitudinal direction, while the others have local structures (seen by only one or two radars).

磁気圏急圧縮 (SC) は、主に低緯度における地上磁場の H 成分の急激な増大として観測される。過去の研究により、SC は太陽風動圧の増大に伴って磁気圏が急激に圧縮されることが原因であると知られている。中緯度や高緯度においては、SC は 2 つの渦構造を持つ電離圏電流を引き起こす。SC に関連して起こる電離圏電流や電離圏電場の擾乱は、地上磁場での観測により、極性の異なる Preliminary Impulse (PI) と Main Impulse (MI) からなる 2 つの変動の重ね合わせによって説明がされている。一方で、SC に関連して起こる電離圏電場の擾乱のいくつかは、PI と MI の変動だけではなく、MI の後に数十分に渡って減衰振動が起こる場合があることが過去の研究で報告されている。また、SuperDARN レーダーによる電離圏観測でも減衰振動が観測されるという報告がある。このように SC に関連して起こる擾乱は、PI、MI の変動のみで終了する場合と、MI の後に減衰する振動が観測されるという 2 つのパターンがあるが、その違いが生じる原因はまだ解明されていない。従って、本研究では、北半球の SuperDARN レーダーを用いて、SC に関連して起こる電離圏電場の振動の原因を探ることを目的としている。2011 年の 1 月から 2015 年の 12 月の 5 年間について調べたところ、244 個の SC イベントが同定され、それぞれのイベントについて、少なくとも 1 つのレーダーで振動が観測された SC イベントは 61 個が同定された。

183 個の PI、MI のみの変動と 61 個の振動イベントを比較した結果、太陽風動圧の増加量の平均値には明確な違いが見られなかった。電離圏電場の振動の磁気地方時（MLT）依存性に関しては、15:00 MLT から 18:00 MLT にかけて発生確率がやや高いという結果が得られた。また、季節依存性を見ると、冬よりも夏に発生確率が下がる傾向にあることがわかった。一方で、個々の振動イベントについて詳細に調べた結果、振動が経度方向にグローバルな広がりを持っている場合や、一方で局所的な構造を持って振動をしている場合があることが判明した。このような振動のグローバル構造、局所的な構造に関しても議論をする予定である。

Statistical study of Ionospheric Conductivity (SZA) Dependence of the SAPS using the SuperDARN Hokkaido East HF Radar

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In this study, we investigate characteristics of the subauroral polarization streams (SAPS), focusing on the solar zenith angle(SZA) dependence using the Super Dual Auroral Radar Network (SuperDARN) Hokkaido East radar, National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellites (POES) system and Meteorological Operational Satellite Program of Europe (MetOp) system data. The time span for the present study is from 2008/1/10 to 2016/12/31, which contains over 3180 days, and we limited the time range of the analysis to 3-8 UT (12-17 LT). We found 60 SAPS events over seasons except for summer, and for each event we examined the SZA and the peak Line-of-sight velocity observed in the SAPS, in order to identify the threshold of the possible SZA and illuminated ionospheric altitude for SAPS to be generated. To the best of our knowledge, this is the first detailed study of SAPS-associated SZA. As a result of the statistical study, we find that SAPS tend to appear when the SZA is larger than 98.5 degrees, and that the minimal threshold of illuminated ionospheric altitude for SAPS occurrence is about 100 km, which is near the altitude of the peak of Pedersen conductivity. This result suggests that the Pedersen conductivity plays an important role in the generation of SAPS. We should take into account the effect of HF propagation geometry, and EUV absorption in the atmosphere. We also need to study inter-hemispheric conjugacy of SAPS using the SuperDARN Buckland Park HF Radar whose location is roughly conjugate to SuperDARN Hokkaido East HF Radar, in order to study further the conductivity dependence.

Ionospheric convection during disturbed periods observed by the SuperDARN radars in the premidnight and postmidnight sectors

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Sub-Auroral Polarization Streams (SAPS) are one of the main disturbance signatures in the ionospheric convection at subauroral latitudes. Their generation is related to a wide variety of factors such as ring current distribution, solar wind / magnetospheric conditions, ionospheric conductivity etc. Expansion of the Super Dual Auroral Radar Network (SuperDARN) field of view into mid-latitudes and the launch of the inner magnetosphere spacecraft made it possible to study the SAPS dynamics in the framework of the global convection and magnetospheric disturbances. In this paper we discuss one event of the SAPS and concurrent convection signatures on Apr 4, 2017, observed by the mid-latitude SuperDARN radars. Together with the enhancement / decay of the SAPS in the premidnight sector, the mid-latitude SuperDARN radar observed the intensification / weakening of the eastward convective flows in the postmidnight sector. Furthermore, these eastward flows were enhanced together with the magnetic perturbations observed by the ERG / Arase satellite located in the same local time sector, probably associated with the substorm expansion onset. Detailed study of the ionospheric convection dynamics including SAPS, as well as their relation to solar wind / IMF condition changes, or substorm / storm developments will be reported.

SuperDARN 2点でSC時に同時観測された磁力線共鳴現象からのプラズマ圏密度推定

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Plasmaspheric mass-density estimation from an FLR event simultaneously observed by two SuperDARN radars

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Geomagnetic pulsations include field-line eigen-oscillations generated by the field-line resonance (FLR). Their frequencies depend on the plasma density along the field line. The FLR frequency is expected to change sharply across the plasmapause, because of the sharp density change there. Since the pulsations oscillate the ionospheric plasma, too, there could exist cases in which SuperDARN radars monitor the two-dimensional (2D) distribution of the FLR frequency, from which we can estimate 2D plasma-density distribution on the magnetospheric equatorial plane, including the 2D location of the plasmapause. We have been looking for such cases in the data from the SuperDARN Radars near the occurrence times of Sudden Commencements (SCs), which are known to frequently cause pulsations.

In this paper we present a case in which, at the time of an SC, two SuperDARN radars simultaneously observed plasma-flow oscillations whose amplitudes and phases had latitude dependence typical to the FLR. The field-of-views of the two radars overlap, and thus it is possible that 2D features, such as the 2D flow directions, of the oscillations are estimated. From thus obtained information, it is possible that 2D plasma density distribution is estimated with high precision. More details will be presented at the meeting.

月付近からの地球磁気圏X線撮像計画 GEO-X

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GEO-X : X-ray imaging of the Earth’s magnetosphere

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We present status of a future Japanese X-ray micro satellite mission concept GEO-X (GEOspace X-ray imager). X-rays are emitted from the Earth’s magnetosphere via solar wind charge exchange.

GEO-X aims at first X-ray imaging of the Earth’s magnetosphere, especially structures of the dayside boundary such as cusps and magnetosheath. A compact and light-weight X- ray imaging spectrometer is being developed and the satellite bus system is being designed.

With GEO-X, we can obtain information on response of the Earth’s magnetosphere to solar winds, chemical composition of solar winds, spatial distribution of geocorona, and also foreground emission for X-ray astronomical observations.

我々は地球磁気圏の昼側境界面 (カスプやシース) を高解像度 (<0.1 地球半径) かつ高時間分解能 (<1 時間以下) で撮像する GEO-X 計画の検討を進めている。磁気圏に捕捉された太陽風イオンは地球から流出した高層大気と衝突し、X線を発光する。独自の超軽量 X 線望遠鏡とピクセル型半導体イメージャーを組み合わせ、視野 4 deg 角、角度分解能 9 分角以下、エネルギー 0.3–2 keV を実現し、月付近から俯瞰的に観測を行う。X 線発光から地球磁気圏の形状、太陽風イオンの組成、地球から流出した大気の分布、さらには X 線天文観測の前景放射の情報が得られる。すなわ ち GEO-X は 4 分野にまたがる横断的ミッションであり、最初のステップとして超小型衛星による実証を目指している。

地球マグネットシースおよび磁気圏内における多点衛星観測データを用いた波動ベクトル解析の有効性について

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Validities of wave vector analysis techniques using multi-spacecraft observation in the magnetosheath and magnetosphere

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There are some difficulties in identifying wave vectors uniquely even if their wave modes are assumed. Wave vector analysis techniques utilizing multi-spacecraft observations have been developed in this decade [e.g., Narita, 2017]. Recent Magnetospheric Multiscale (MMS) mission enable us to resolve smaller wavelength in the ion kinetic range. It is important to assess the validities of the wave vector analysis techniques utilizing multi-spacecraft observations. We applied several techniques to synthetic and observed data.

The wave telescope or k-filtering techniques [Neubauer and Glassmeier, 1990; Narita et al., 2011] are based on the direction of arrival estimation by array antennas. Gershman et al. [2017] performed Bellan's method in which pre-Maxwell Ampere's law is assumed [Bellan, 2016] with use of the current density determined by the curlometer technique [Dunlop et al., 2002]. These techniques can provide the wave vectors with a high accuracy, though not always. The accuracy depends on specific parameters and situations, e.g., the wave vector direction with respect to the spacecraft formation. The frequency-wave vector distributions estimated using observed data by MMS in the magnetosheath and magnetosphere well agree with those calculated by the linear theory, but tend to disagree when the spacecraft are close to the wave sources.

Structure of the Hall magnetic field in dayside magnetic reconnection inferred from MMS data

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Magnetic reconnection is one of the most important processes for understanding the interaction of the solar wind with Earth's magnetosphere. In the Earth's magnetosphere magnetic reconnection can occur at the dayside magnetopause and magnetotail. It is known that the asymmetric reconnection tends to occur at the dayside magnetopause because of the properties of the magnetospheric and solar wind plasmas. In previous simulations of asymmetric reconnection, the bipolar pattern of the Hall magnetic field is suggested. The observations by Magnetospheric Multiscale (MMS) mission have revealed that there is quadrupolar pattern of the Hall magnetic field in the dayside asymmetric reconnection.In this study, we analyze several reconnection events to improve our understanding the Hall reconnection pattern by using MMS data. In addition, we focus on current system to confirm the relationship between the Hall current and the Hall magnetic field in each pattern. We find both quadrupolar and bipolar patterns. In the quadrupolar pattern, the Hall magnetic field has two peaks in the ion diffusion region. On the other hand, in the bipolar pattern, the Hall magnetic field has one peak. We also confirm that the Hall currents generated by ion and electron flows produce the Hall magnetic field.Furthermore, we reveal that the Hall magnetic field of bipolar pattern can be classified as two types. In each type, the position where the Hall magnetic field peaks and the Hall current reverses is different. In first type, the position is between electron inflow region in the magnetospheric side and electron outflow region. In second type, the position is between electron outflow region and electron inflow region in the magnetosheath side or inside the electron outflow region.From this result, we consider that asymmetric properties influence not only the contribution of inflow in the magnetospheric side to the Hall current but also the variety of electron flows in the ion diffusion region.

Outflowing Ion Ring Distributions and their Correlation with Low-Frequency Wave Spectra Observed in/near the PSBL by MMS

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We report the recent findings of the ring-type velocity distribution functions of the outflowing ions and their correlation with the low-frequency wave spectra observed in/near the plasma sheet boundary layers(PSBLs) by the NASA MMS(Magnetospheric Multiscale) spacecraft during the magnetotail crossing phase in 2016. It is most likely that the tailward-flowing ion beams in the tail lobe/mantle regions at the distance of about 10 Re would be energized in the directions perpendicular to the local magnetic fields through the wave-particle interaction in the gyro-frequency ranges due to the plasma wave activities enhanced in the PSBL before these ion components are injected into the plasma sheet. The ion composition measurements discriminating the ions species have been done by the HPCA (Hot Plasma Composition Analyzer), which could provide us with the 3-dimensional velocity distribution functions about every 30 seconds at the slowest. The fluxgate magnetometer data of three magnetic field components are also available with 128 Hz based on the observations by the FGM on an extended mast. The gyro-frequencies of the ions in the PSBL are less than 1 Hz even for protons, and the fluxgate magnetometer data indicate that the spectra of lower-frequency waves are more intensified particularly in the PSBL probably because of the two-beam instability caused by high-speed counter streams of proton in the PSBL. In this presentation, we exhibit some events based on the HPCA and FGM observations in the mid-distance magnetotail in the MMS dataset for discussing the wave-particle interaction mechanisms acting on the outflowing ion beams in/near the PSBL. These observational results imply that the wave-particle interaction would play an important role also in the plasma energization of the outflowing ions of ionospheric origin in the PSBL and their transport from the magnetotail lobe/mantle to the plasma sheet while the transversely accelerated ions caused by the wave-particle interaction processes have frequently been observed by a number of polar-orbiting satellites in the auroral magnetosphere. It is getting more obvious that the comprehensive research for the wave-particle interaction mechanisms in the space plasmas would be more essential and universal in the space physics and any relevant research fields.

Two-dimensional electromagnetic particle simulation of whistler-mode triggered emissions

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We perform two-dimensional electromagnetic particle simulations to study basic characteristics of whistler-mode wave particle interaction involved in chorus emissions propagating oblique to the static magnetic field. We assume a simple periodic (x, y) system with the magnetic field taken in the x-direction. Assuming energetic electrons with an anisotropic bi-Maxwellian velocity distribution function, we first test the linear whistler-mode instability driven by temperature anisotropy to confirm the numerical property of the simulation code. With the electrostatic components parallel to the magnetic field, which have been neglected in the previous simulation studies on chorus emissions, we find the linear phase of the instability is much affected by the Electrostatic thermal fluctuations. It is necessary to put many super-particles in a grid cell to suppress the thermal fluctuation. With 30,000 particles per cell, we have confirmed a good agreement of the wave growth in the parallel direction with the linear growth rate. We next put an array of antennas with obliquely aligned to uniform magnetic field, and oscillate the antenna current with a variable frequency below the electron cyclotron frequency to excite a large amplitude whistler-mode wave obliquely propagating to the static magnetic field. In addition to the nonlinear trapping of energetic electrons through the cyclotron resonance, another nonlinear trapping of electrons by the Landau resonance takes place. Structures of the nonlinear trapping potentials changes with a varying frequency, affecting the efficiency of energy transfer between the wave and energetic electrons. We study nonlinear evolution of the wave packet, and competing processes of both resonances in accelerating the energetic electrons to higher energies.

Nonlinear damping of oblique whistler mode waves through Landau resonance

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Nonlinear trapping of electrons through Landau resonance is a characteristic dynamics in oblique whistler-mode wave particle interactions. The resonance velocity of the Landau resonance at quasi-parallel propagation becomes very close to the parallel group velocity of whistler-mode wave at frequency around 0.5 f_{ce}, causing a long distance of resonant interaction and strong acceleration of resonant electrons (Hsieh and Omura, 2017). We demonstrate these effective accelerations for electrons with high equatorial pitch angle (greater than 60 degrees) by test particle simulations with parameters for the Earth's inner magnetosphere at L=5. In the simulations, we focus on slightly oblique whistler mode waves with wave normal angle less than 20 degrees. Analyzing the wave electric field **E** and the resonant current **J**, which is composed of electrons undergoing the Landau resonance, we find that the **J** dot **E** is mainly positive, which denotes the damping of the wave. Furthermore, we confirm that this positive **J** dot **E** is dominated by transverse component $\mathbf{J}_{perp}$ dot $\mathbf{E}_{perp}$ rather than by longitudinal component $\mathbf{J}_{para}$ dot $\mathbf{E}_{para}$. The simulation results reveal that the Landau resonance contributes to the nonlinear damping at 0.5 f_{ce} for whistler mode waves.

Pitch Angle Scattering of Energetic Electrons by Plasmaspheric Hiss Emissions

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We study scattering of energetic electrons in pitch angles and kinetic energies through their resonance with plasmaspheric hiss emissions consisting of many coherent discrete whistler-mode wave packets with rising and falling frequencies. Using test particle simulations, we evaluate the efficiency of scattering, which depends on the inhomogeneity ratio S of whistler mode wave-particle interaction. The value of S is determined by the wave amplitude, frequency sweep rate, and the gradient of the background magnetic field. We first modulate those parameters and observe variations of pitch angles and kinetic energies of electrons with a single wave under various S values so as to obtain basic understanding. We then include many waves into the system to simulate plasmaspheric hiss emissions. As the wave packets propagate away from the magnetic equator, the nonlinear trapping potential at the resonance velocity is deformed, making a channel of gyrophase for untrapped electrons to cross the resonance velocity, and causing modulations in their pitch angles and kinetic energies. We find efficient scattering of pitch angles and kinetic energies because of coherent nonlinear wave-particle interaction, resulting in electron precipitations into the polar atmosphere. We compare the results with the bounce averaged pitch angle diffusion coefficient D_{aa} based on quasi-linear theory, and show that the nonlinear wave model with many coherent packets can cause scattering of resonant electrons much faster than the quasi-linear diffusion process.

信号処理による自然波動現象からのパルス性雑音除去

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Impulse noise reduction techniques using audio signal processing for natural electromagnetic waves

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We have been conducting the ground-based observations of VLF emissions (100 Hz to tens of kHz) at the sub-auroral latitudes. The ground-based observations can continuously measure VLF emissions at a fixed L with a high time resolution. However, the observed data include various kinds of noises added during the long wave propagation. In order to reduce the effect of the noises, we have applied noise reduction techniques based on audio signal processing. The observed data include the stationary (white noise and hum noise etc.) and impulse noises (atmospheric noise and artificial clock noise etc.). In our previous study, we developed a stationary noise reduction technique by using spectral subtraction method and an adaptive filter. The simulation results showed that the input signal-to-noise ratio was improved by more than 10 dB.

In this study, we have developed an impulse noise reduction technique. It is difficult to extract VLF emissions above 5 kHz (such as auroral hiss) because the impulsive lightning sferics are dominant in this frequency range. For the artificial impulsive noise, such as the one caused by GPS pulses, we can estimate a standard model of digital clock waveform. However, it is difficult to apply the standard waveform model to sferics, because natural impulsive noises cannot by expressed as autoregressive models. A sferic pulse is much shorter than a VLF emission. So we use an averaged spectrum intensity from the data before and after the sferic pulse to interpolate the spectrum intensity. It is important to detect sferic pulse with a high accuracy to interpolate the data. We used test signals consisting of simulated sferic pulses, hum noises (saw-tooth waves), and white noises to evaluate the detection performance of sferics. We detected sferic pulses using a fixed threshold amplitude. The detection results showed 20% false detection for using the original test signals and 4% false detection for using high-pass-filtered (cutoff frequency of 5 kHz) test signals. By reducing hum noises with the high-pass filter, the detection accuracy was improved. In the future, we will consider the use of the neural network to further improve the detection performance of sferics.

In this presentation, we will discuss our noise reduction techniques for the VLF emissions in detail. The proposed noise reduction methods by using audio signal techniques can be applied not only to VLF but also to ULF waves. We believe that this study can be significantly contributed to reduction in the cost and time for a conventional EMC test.

磁気圏で観測される VLF エミッションは、高エネルギー粒子のピッチ角散乱や加速に大きく寄与している。我々は、磁力線で放射線帯とつながるサブオーロラ帯にて VLF エミッション（10 Hz〜数十 kHz）の地上連続多地点観測を行っている。地上観測は、衛星観測と比較して電磁波動現象を固定の L 値かつ高い時間分解能で連続観測できる利点がある。しかし、地上観測は観測機器や伝搬経路で生じた雑音が含まれる欠点がある。これまでは、EMC 試験や僻地での観測を行うといった方法を行ってきたが、コスト面での課題があった。そのため、我々は VLF エミッションが可聴周波数帯域であることに着目し、音声信号処理技術による雑音除去の検討を行っている。電磁波動現象の伝搬経路で生じる雑音は、定常雑音（白色雑音やライン雑音など）とパルス性雑音（空電や機器のクロック雑音など）の 2 種類がある。定常雑音に関しては、スペクトルサブトラクション法や適応フィルタなど、音声信号処理の分野で一般的に扱われる方法を用いることで、10dB 以上 SN 比を改善できることをシミュレーションによって確認することができた。

本研究では特にパルス雑音除去について検討を進めた。空電は 5 kHz 以上の周波数帯で頻繁に（1 秒間に 100 回程度）発生しており、同様の周波数帯で発生している VLF エミッションが空電に埋もれてしまう。空電の混入は僻地観測や EMC 試験で改善できるものでないため、信号処理で空電を除去し、オーロラヒスなどの VLF エミッションを抽出することを検討した。GPS パルスなどに起因するクロック雑音は、人工雑音のため標準モデルを推定することができるが、自然現象によって発生する空電は、自己回帰モデルで近似出来ないため標準モデルを推定することが困難である。そのため、本研究では標準モデルを使用せずに空電を除去した。VLF エミッションの数秒の存続時間に対して空電は 1〜3 ms 程度でごく僅かな時間幅であることから、空電が存在する区間のスペクトル強度は空電が発生していない前後の平均スペクトル強度として補間することが可能である。この手法を効果的に扱うためには、空電を高い精度で検出することが重要である。空電は波形の振幅の閾値を利用して空電を検出している。空電は通常 5 kHz 以上の周波数帯で見られるため、カットオフ周波数 5 kHz の HPF を用いることで検出率が 30%程度向上する結果を得た。今後は、閾値で検出した部分を機械学習で空電とそれ以外を識別することで、空電の検出精度をさらに向上させることを検討している。

今回提案した音声信号処理技術による雑音除去手法は、VLF 帯だけでなく、誘導磁力計で観測した ULF 帯の信号など様々な観測信号に適用させることができる。観測信号に含まれる雑音を除去することで、電磁波動現象の解明に大きく貢献できると考えている。

アナログ・デジタル混載チップによる小型プラズマ波動波形捕捉受信器

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Small Plasma Waveform Capture Receiver by using analog-digital mixed chip

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Space is filled with subtle plasma, so-called space plasma. Since space plasma is basically collisionless, plasma particles exchange their own kinetic energies and moments through plasma waves. Observing plasma waves allows us to understand physical processes occurring in the space plasma. That is why plasma wave receivers have been installed in many satellites which explore the space environment. On the other hand, the necessity of the simultaneous observations with multiple satellites is widely recognized in order to separate spatiotemporal variation of phenomena. However, it is difficult to execute multiple satellite missions using the conventional medium and large size of satellites, because of the limitation of the resources for launching. The way to break this restriction is to use small, or ultra-small satellites. The number of launching small or ultra-small satellite in recent years is increasing. However, since plasma wave receivers require a plenty of resources in their size and weight, they do not meet the limited resource of small satellites or ultra-small satellites.

In order to reduce the required resource for plasma wave receivers, our research group has been attempting to miniaturize plasma wave receivers using ASIC (Application Specific Integrated Circuit) technology.

There are two types of plasma wave receivers. They are a waveform capture receiver and a spectrum receiver. They are composed of analog circuits, digital circuits, and A / D converters. The analog circuits consist of various kinds of filters and amplifiers. The main roles of the digital circuits are an FFT calculation in the spectrum receiver, and a data compression in the waveform capture receiver.

In the present paper, we focus on the development of a small waveform capture receiver based on an analog-digital mixed chip. The waveform capture receiver is a receiver to acquire the waveform data of plasma waves. The amount of original waveform date is large, so it is impossible to send to the ground station continuously. Since in order to increase the number of the shots of observations, it is necessary to reduce the data size, the data compression by the digital circuits is crucial.

In a previous study, the design of the ASIC implementing analog circuits of both spectral type and waveform capture type plasma wave receivers have been already conducted. From this study, we succeeded in greatly miniaturizing the plasma wave receiver. Moreover, on the part of the digital processing, we succeeded in the hardware design on the FPGA developed by Kanazawa University. Based on these technologies, our research introduces the data compression logic implemented on the FPGA with an analog-digital hybrid technology in an ASIC chip that implements the analog section. The target of our research is to achieve the ultimate miniaturization by putting both analog part and digital part which are in the waveform capture type receiver into one chip.

The logic configuration of the FPGA can be used as well as ASIC one. It is possible to develop ASIC based on HDL (Hardware Description Language) data. We develop the design of the ASIC with waveform compression circuits based on HDL. The designed logic is installed on the same chip in which the analogue circuit of the waveform revceiver.

In this presentation, we present the details of the waveform compression logic design in the waveform capture receivers realized on the ASIC. Moreover, we explain the results of its operation verification, and guidelines for further development as a more advanced waveform capture receiver in the future.

宇宙空間は希薄なプラズマで満たされており、その運動エネルギーの交換は波動として観測される。つまりプラズマ波動を観測することで、宇宙プラズマ中で生起する物理素過程を知ることが出来る。このため、宇宙空間環境を探査する衛星には、必ずプラズマ波動受信器が搭載されてきた。一方で、現象の時空間変化を分離するために、複数の衛星で同時に観測する必要性が広く認識されているが、従来の中型・大型衛星では、そのリソースの制限が同時に複数衛星を打ち上げるには限界がある。この限界を打破できるのが、近年打ち上げ数が増えている小型、超小型衛星の利用である。しかし、プラズマ波動受信器は小型の衛星に搭載するには大きく、このままでは小型の衛星に搭載することはできない。

そのため、本研究グループは、ASIC(Application Specific Integrated Circuit) 技術を用いたプラズマ波動受信器の小型化を目指している。

プラズマ波動受信器には波形捕捉型とスペクトル型の 2 種類があり、それぞれアナログ回路およびデジタル回路、A/D 変換器で構成されている。アナログ回路は各種フィルタとアンプで構成されている。デジタル回路では、スペクトル型では FFT、波形捕捉型では、波形圧縮回路がコアとなる。

本研究では、ASIC 技術による小型波形捕捉型受信器の開発を進めている。波形捕捉型受信器はプラズマ波動の波形データを取得する受信器である。波形データはそのままでは地上に送信するにはデータ量が大きく、連続的な観測が行えない。観測回数を増やすために、少しでもデータを小さくする必要があり、デジタル処理によるデータ圧縮が必要で

ある。この波形データのデジタル処理による圧縮をハードウェアとして行う回路が波形圧縮回路である。

本研究の先行研究として、プラズマ波動受信器のスペクトル型、波形捕捉型双方のアナログ回路の ASIC 化を実現している。これにより、プラズマ波動受信器アナログ回路の大幅な小型化に成功した。また、デジタル処理部についても、金沢大学のグループにより従来ソフトウェアで実現されていた処理のハードウェア化 (FPGA 化) にも成功している。そして、それらの技術を基盤に

本研究では、アナログ部をインプリメントした ASIC チップ内に、アナログ・デジタル混載技術を用いて、FPGA 上で実現されたロジックを導入する。そして、波形捕捉型受信器のアナログ部、デジタル部をすべて一つにチップ化して究極の小型化をはかることを目的としている。

ASIC で使用される論理構成は FPGA と同一のものを使用することが出来る。したがって、FPGA ですでに、開発および検証済の HDL(Hardware Description Language) データをもとに ASIC を開発することが出来る。金沢大学で FPGA 用に開発、検証された HDL をもとに波形圧縮回路の ASIC 化を行う。

本発表では波形捕捉型受信器のうち、ASIC 上に実現した波形圧縮ロジック設計の詳細とその動作検証結果について発表を行い、今後更に高度な波形捕捉型受信器として開発を進める指針を示す。

惑星間空間衝撃波到来による放射線帯電子への影響

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Impact of interplanetaly shock on electrons in the inner magnetosphere

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Interplanetary (IP) shock is known to disturb energetic trapped electrons adiabatically and non-adiabatically in the inner magnetosphere. Growth of the whistler mode chorus waves are known to occur where electron anisotropy in the keV-range is large. To understand the adiabatic and non-adiabatic processes in response to the IP shock, we need to track the overall evolution of the electrons from keV to MeV ranges. We used the global magnetohydrodynamics (MHD) simulation and drift advection simulation (CIMI). We used the AE8 model for the electrons with energy greater than 40 keV, and the kappa distribution with energy less than 40 keV as the initial condition of the phase space density of the trapped electrons. We changed the parameter E_0 that corresponds to temperature of the electrons from 0.5 keV to 10 keV. We obtained the following results. 1) The temperature anisotropy (=1-Tperp/Tpara) increases to 0.3. The temperature anisotropy seems not to depend on E_0. 2) The convection electric field increases when the southward interplanetary magnetic field follows the interplanetary shock. The electrons with energy at the keV to 10 keV range are transported inward. The flux of the electron seems to depend on E_0. 3) When a substorm expansion starts, the electrons are transported inward together with electrons newly injected from the nightside plasma sheet.

惑星間空間衝撃波によって磁気圏内における電子が断熱的に加速・輸送されることは良く知られている。一方、ホイッスラーモードコーラス波動との相互作用によって非断熱的に加速・散乱される可能性も指摘されている。ホイッスラーモードコーラス波動は keV 帯の電子の温度異方性によって励起されると考えられているため、惑星間空間衝撃波に対する放射線帯電子への影響を理解するためには、keV 帯から MeV 帯にかけての広いエネルギー範囲について断熱過程と非断熱過程を把握する必要がある。今回は３次元グローバル電磁流体（MHD）シミュレーションと電子の移流シミュレーション（CIMI）を用い、理想的な太陽風パラメータを与え、内部磁気圏電子の応答過程を調べた。移流シミュレーションの初期条件として、40 keV 以上の電子の位相空間密度については経験モデルである AE8 を、それ以下の電子の位相空間密度についてはカッパ分布を仮定した。温度に相当するパラメータ E_0 を 0.5 keV から 10 keV に変化させ、初期状態への依存性を調査した。結果は以下のとおりである。 1) 惑星間空間衝撃波到来直後、温度異方性は磁気圏前面で 0.3 まで上昇した。温度異方性は E_0 に依存しない。2) 惑星間空間衝撃波の直後に南向きの惑星間空間磁場 (IMF) が含まれると対流電場が強まり、1~10 keV 帯の電子は地球方向に輸送される。この電子フラックスは E_0 に大きく依存する。3) サブストーム拡大相の開始に伴い、これらの電子は新しく夜側から流入した電子とともに更に内側に運ばれる。

あけぼの衛星観測に基づく昼側カスプ領域における ELF 帯電磁波による水素・酸素イオン加熱の解析

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H+ and O+ ion heating by electromagnetic ELF waves in the dayside cusp region based on Akebono observation

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The Earth's dayside cusp region is one of main origins of ion outflow. Ground, rockets, satellites observations reported ion heating/acceleration like transversely accelerated ions (TAI) and ion conics with simultaneously bipolar electric field and plasma waves which contribute to ion heating/acceleration in region from the ionosphere to the magnetosphere within a geocentric distance of several Re. [Chaston et al. 2004; Waare et al., 2012; Lund et al., 2012]

Broadband Extremely Low Frequency waves (BBELF), which enhance in wide frequency range in ELF bands, is one of such plasma waves observed in the dayside cusp. Kasahara et al. [2001] reported that BBELF was observed with more strong intensity in the dayside cusp than in other latitude and MLT region, and that it was observed in altitudes range from 275 km to 10,500 km in the dayside cusp by the Akebono satellite. They also reported that BBELF consisted of two components, the electrostatic component up to proton gyrofrequency or lower hybrid frequency and the electromagnetic component below oxygen ion gyrofrequency. Moreover, they indicated that there was correlation between energy density of TAI and ion conics heated up to 100eV and electric field spectral density of BBELF below 10 Hz, which is lower than proton and oxygen ion gyrofrequencies, and that heated ions were found only when the electric field spectral density of BBELF is larger than the threshold intensity of 0.1 $[(mV/m)^2]$.

In the analysis of correlation between TAI and ion conics and electric field of BBELF by Kasahara et al. [2001], ions were not divided by their species. In this study, we divide H^+ and O^+ ions using data from ion mass spectrometer, and investigate the correlation with intensity of BBELF below oxygen ion gyrofrequency. We use datasets of thermal ions below 25 eV and electromagnetic field in a frequency range from 3.18 Hz to 17.8 kHz observed by Akebono Suprathermal Ion Mass spectromter (SMS) and VLF Multichannel Analyzer (MCA) in the dayside cusp in a sector of 10-14 MLT and in invariant latitude of 65-80 degree. Data selection criteria are as follows: Increase of magnetic field intensity of BBELF below oxygen ion gyrofrequency from the average is more than 2sigma, and the ion counts of 4 channels in perpendicular directions with respect to earth's magnetic field or all channels enhance. As a result of statistical analysis of H^+ and O^+ ions heating in an altitude of 4000-8000km in a period from January to February, 1990, we found that the counts of heated H^+ and a part of O^+ ions showed positive correlation with electric field spectral density. However, the counts of the other part of O^+ ions did not show clear correlation. The threshold intensity of BBELF as reported by Kasahara et al. [2001] was also found in this study. The threshold intensity of BBELF for H^+ ions was $0.1[(mV/m)^2]$, as large as reported. However, the threshold intensity of BBELF for O^+ ions was $0.01[(mV/m)^2]$, less than that for H^+ ions.

Our results suggest that the correlation between heated ions and BBELF intensity reported by Kasahara et al. [2001] mainly indicated the correlation between heated H+ ions and BBELF intensity, and that O+ ions are heated more efficiently by BBELF.

In order to clarify the mechanism of the threshold as shown in this study, we are going to perform further analysis of heating events of each ion in consideration of other parameters such as ion temperature and density, which affect the threshold level. Singh et al. [2007] reported based on particle simulation that the electrostatic wave was generated by the relative drift between light and heavy ions accelerated by the electromagnetic component of BBELF and that it accelerated ions. We can understand that the two-step acceleration suggested by the simulation generates the threshold. We are also going to perform event analysis and comparison with the physical process in the simulation.

地球の昼側カスプ領域は電離圏のイオンを磁気圏に供給するイオンアウトフローの発生源のひとつとして重要な役割を担っていると考えられている。地上やロケット、衛星観測により電離圏高度から磁気圏の数 Re まで、磁場の垂直方向に加熱されるイオン（TAI）やイオンコニックスなどのイオン加熱、加速現象と同時に、電場の存在や波動の増大が観測されており、幅広い高度で電場や波動などによりイオン加熱、加速が起き、電離圏イオンが磁気圏に流出していると考えられている。[Chaston et al. 2004; Waare et al., 2012; Lund et al., 2012]

イオン加熱域で観測される波動現象の 1 つとして、BloadBand Extremely Low Frequency （BBELF）と呼ばれる広帯域 ELF 波動の強度増大が報告されている。あけぼの衛星の観測により、BBELF は他の緯度、MLT 領域と比較し、昼側カスプ領域で 275km から 10500km までの幅広い高度帯で、とくに強い強度で観測されていた。また、H^+ のサイクロトロン周波数または低域混成周波数付近まで広帯域に現れる静電成分と O^+ のサイクロトロン周波数以下に現れる電磁波成分が観測されており、静電波と電磁波の両者が混在していることも示されている。さらに、高度 3000km 以上で 100eV 以上の十分に加熱された TAI やイオンコニックスと H+のサイクロトロン周波数を下回る 10Hz 以下の電場スペクトル強度

との相関も報告されており、この周波数帯の波動が H^+ を主成分とするイオンの加熱に寄与している可能性が示唆された。加えて、電場スペクトル強度がおよそ 0.1[$(mV/m)^2$] の閾値を超える場合において効率的にイオンが加熱されることも報告された。[Kasahara et al., 2001]

本研究では、Kasahara et al. [2001] でイオン種を区別しない解析の結果得られた TAI やイオンコニックスと 10Hz 以下の電場スペクトル強度との相関について、O^+ のサイクロトロン周波数以下に現れる電磁波によるイオン種ごとの加熱に着目するため、あけぼの衛星に搭載された VLF 観測装置のサブシステム Multichannel Analyzer（MCA）で観測された 3.18Hz から 17.8kHz の波動の電磁波成分のデータと Suprathermal Ion Mass spectrum（SMS）で観測された 25eV 以下の熱的イオンのデータを用いて、10-14MLT、磁気緯度 65-80 度の昼側カスプ領域において磁場強度が前後 1 時間の平均値より 2 シグマ以上増大し、かつイオンのカウント数が磁力線垂直方向の 4 チャンネルまたはすべてのチャンネルの合計で増大したイベントを統計的に解析した。1990 年 1、2 月の高度 4000-8000km のデータで統計解析を行った結果、H^+ および O+の一部でイオンのカウント数と電場スペクトル密度に正の相関がみられた。しかしながら O^+ では、イオンのカウント数と電場スペクトル密度に明確な相関がみられないイベントが見られた。また、H^+ は Kasahara et al. [2001] と同様に電場スペクトル強度が 0.1[$(mV/m)^2$] の閾値を超える場合に効率的にイオンが加熱されていたが、波動と相関を示す O^+ は H^+ と異なって電場スペクトル強度が 0.01[$(mV/m)^2$] の閾値を超える場合に効率的にイオンが加熱されていた。これらの解析結果から、Kasahara et al. [2001] で示された相関が、主成分を占める H^+ の加熱の特性を反映したものだったこと、少数成分ながら O+が H+より低い 0.01[$(mV/m)^2$] の閾値以上でより効率的に加熱されている可能性が示唆された。

粒子シミュレーションによって、電磁波の磁力線に垂直な電場成分によって H^+ と O^+ の間に速度の異なるドリフトが生じ、それらの速度差によって生じた静電波がイオンをさらに加速することが示唆されている。[Singh et al., 2007]

このような電磁波と静電波の二段階の加速により、閾値が生じている可能性が考えられ、今後、イベントごとにシミュレーションの条件と比較し、波動の成長やイオン加熱の物理プロセスを検討していきたい。また、解析イベント数を増やすとともに、波動の成長や加熱の効率など閾値に影響を与えると考えられるイオン温度や密度などその他のパラメータを変化させるような条件で分類した統計解析を行い、イオン種ごとに加熱の閾値や相関の有無が生じるメカニズムを議論していきたい。

Imbalance between the electron and ion precipitations in the cusp for northward IMF

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When IMF is northward, magnetosheath electrons and ions are injected into the cusp via high-latitude reconnection poleward of the cusp. The injected ions (protons) often produce the spot-like proton aurora at 75 - 85 MLAT in the dayside ionosphere, and the brightness of the proton aurora increases during intervals of high solar wind dynamic pressure. In this research we examine the features of the cusp electron precipitation for northward IMF using observations of cusp auroras from an all-sky imager at Longyearbyen, Svalbard, and in situ observations from the DMSP spacecraft. We analyzed the 630 nm auroral image data from the all-sky imager and the precipitating particles and ion drift data from the DMSP spacecraft. The simultaneous observations from the all-sky imager and the DMSP spacecraft during intervals of high solar wind dynamic pressure reveal that the precipitating electron energy flux is much smaller and less structured than the precipitating ion energy flux in the reverse convection region, producing weak 630 nm auroral emissions in the high-latitude part of the cusp. The statistical analysis of the integral number flux data from the DMSP spacecraft also shows that there exists a prominent imbalance between the electron and ion precipitations for northward IMF. Using solar wind parameters other than dynamic pressure and spatial distributions of the cusp electron precipitation, which is obtained from the aurora data, we discuss what determines the imbalance.

昼側カスプ・マントル沿磁力線電流を駆動する磁気圏ダイナモ

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Magnetospheric dynamo driving the dayside cusp/mantle field-aligned current systems

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The field-aligned current (FAC) systems in the dayside cusp/mantle region are controlled by the dawn-dusk (By) component of the interplanetary magnetic field (IMF). Observations by low-altitude satellites indicate that when IMF By is positive, in the Northern Hemisphere, there appears a pair of FAC sheets flowing into the ionosphere on the equatorward side (midday region 1) and flowing away from the ionosphere on the poleward side (region 0). The flow directions are opposite in the Southern Hemisphere. When IMF By is negative, the above-mentioned flow directions reverse in both hemispheres. Concurrent precipitating particles imply that the midday region 1 on the equatorward side corresponds to the magnetospheric cusp whereas the region 0 on the poleward side corresponds to the plasma mantle. Although this morphology is well established, as for the understanding of the magnetospheric source processes driving those currents, there has been almost no progress in the past two decades. This is because it is very difficult to investigate the physical processes in the magnetosphere from observations. To overcome this difficulty, using the solar wind-magnetosphere-ionosphere simulation code developed by Tanaka [2015] (the Reproduce Plasma Universe (REPPU) code), we examined the dayside FAC systems. We found the following.

(1) Midday region 1 and region 0 currents are closed in the high plasma pressure region in the magnetosphere located at a geocentric distance of about 10 Re (the so-called 'cusp'). The field-perpendicular current connecting the two currents does not simply flow latitudinally but spirally encircles the high-pressure region several times making the current loop coiled.

(2) The poleward side of the high-pressure region is a dynamo (releasing electromagnetic energy) while the equatorward side of the high-pressure region is a load (accumulating electromagnetic energy). The dynamo process is interpreted in terms of expanding slow mode disturbances.

(3) The prenoon or postnoon region 0 current closes with the dawnside or duskside region 1 current in a near-Earth (about 6 Re in geocentric distance) dynamo region. The field-perpendicular current in the dynamo region directly connect the two currents and forms a simple current loop. Thus, the postnoon or prenoon current system is obviously different from the midday current system.

昼側のカスプ・マントル領域に現れる沿磁力線電流系は惑星間空間磁場の朝夕成分（IMF By）に制御される。低高度衛星の観測によると、IMF By が正のときの北半球では、低緯度側では電離圏に入り（midday region 1）高緯度側では電離圏から出る（region 0）2 層 1 組の沿磁力線電流シートが現れる。南半球では電流の向きが逆になる。IMF By が負のときには、両半球とも上述の電流の向きは反転する。降下粒子でみたプラズマ領域との関係は、低緯度側の midday region 1 がカスプに、高緯度側の region 0 がマントルに対応している。これらの現象論はほぼ確立されているが、沿磁力線電流を駆動する磁気圏でのプラズマ過程の理解はこの 20 年間ほとんど進んでいない。その理由は、磁気圏の物理過程を観測から調べることは非常に困難だからである。この困難を克服するため、Tanaka [2015] が開発した太陽風－磁気圏－電離圏系シミュレーションコード（Reproduce Plasma Universe (REPPU) コード）を用いて昼側沿磁力線電流系の再現を行った。その結果以下のことがわかった。

（1）Midday region 1 と region 0 は地心距離 10Re 程度の高圧プラズマ領域（いわゆる「カスプ」）で閉じている。両者を結ぶ垂直電流は単純に緯度方向に流れているのではなく、高圧プラズマ領域を取り囲みらせん状に何度も旋回してコイル状の電流ループを形成する。

（2）高圧領域の高緯度側がダイナモで（電磁エネルギー放出）、低緯度側はロード（電磁エネルギー蓄積）である。ダイナモ過程は膨張する磁気遅進波擾乱で説明できる。

（3）真昼から朝側・夕側に離れた地方時に現れる region 0 は、朝側・夕側の region 1 と比較的地球近くの（地心距離 6Re 程度）ダイナモ領域で閉じている。ダイナモ領域の垂直電流は２つの電流を直接結び、単純な電流ループを形成する。したがって、真昼から離れたところに現れる電流系は真昼に現れる電流系とは明らかに異なる。

カスプの赤道側境界におけるメソスケールのオーロラ増光の経度分布特性

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Characteristics of the longitudinal distribution of mesoscale auroral intensifications near the equatorward boundary of the cusp

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We examined auroral image data from an all-sky imager at Longyearbyen, Svalbard in order to understand when and how the mesoscale auroral intensifications occur near the equatorward boundary of the cusp in the high-latitude ionosphere. Detailed analyses of the data obtained from the intervals when IMF had a southward component show that multiple intensifications tend to occur in the very close MLT meridians within about one minute. We discuss what features of flux transfer events can explain these characteristics.

昼側のカスプ領域では，北向き IMF 時を除くほとんどの場合に，赤色のオーロラが極方向成分をもって移動している．マグネトシースに起源をもつ比較的エネルギーの低い電子の降下が引き起こしているこのようなオーロラの移動は，地上において観測の経度を固定した meridian scanning photometer のデータや全天イメージャーのデータを特定の線で切ったケオグラムにおいて明確に同定され，その性質が明らかにされてきている．例えば，極向きに移動するオーロラの発生間隔は 4 分程度が多いという性質がみられる．本研究では，全天イメージャーの視野内から広く得られるデータをもとに，極向きに移動するオーロラのうち，カスプの赤道側境界においてメソスケールの増光をもつ現象に焦点をあてる．これにより，特定の経度に沿ってオーロラを見ている場合には捉えられなかった複数の経度でほぼ同時に起きる現象も取りあげ，一方，経度方向に長く一様な構造となって極向きに移動するような現象は除くことを意図している．

ロングイャービィエンに設置されている全天イメージャーによって，IMF が南向き成分をもつ期間に得られた 630 nm のオーロラデータを解析した．カスプの赤道側境界の場所とメソスケールの増光の空間サイズに一定の基準を導入して，メソスケールの増光が起きた時刻と MLT を調べた．postnoon 側と prenoon 側での増光のイベント数が大きく異なる IMF By 依存性が広い範囲の MLT でみられることに加えて，1 時間程度の MLT の範囲内での特徴として，特定の MLT で増光が起こると，直後に近傍の MLT で増光が起こる傾向があることは明らかになった．これらの連発現象では，1 分程度の時間間隔が重要であることもわかった．統計的に有意であるかどうかを検討した結果も報告する．また，磁気圏マグネトポースでの flux transfer event のどのような特徴と関連づけられるのかについて議論する．

ヌルによるテーターオーロラの生成

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Magnetic nulls generating the theta aurora

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We investigated the topological structure of magnetic field lines above the theta aurora from the high-resolution simulation. First, we create a quasi-stationary solution under the stationary northward interplanetary magnetic field (IMF) with By-. At this time, the IMF magnitude is somewhat strengthened. Under this condition, 2 null 2 separator structure is obtained. Then the IMF is changed to IMF By +. Soon, the oval in the morning (afternoon) side in the northern (southern) ionosphere peels off toward high latitudes to form the theta bar. A new polar cap appears behind the theta bar. Then, we analyze the solution showing the theta aurora. The topology of the dayside separator line changes little from that before the IMF By reversal. In the northern hemisphere, the null point and stem line move from the morning side to the afternoon side. Magnetic field lines passing through the dayside null point in the northern hemisphere (southern hemisphere) lead to the low latitude edge of the new polar cap that is on the afternoon (morning) side of the southern (northern) ionosphere. On the other hand, the topology of the nightside separator line changes drastically after the IMF By reversal. On this separator line, two new nulls are formed in the tail. These nulls indicate the structure of the saddle point bifurcation null. Magnetic field lines passing through the northern (southern) theta aurora bifurcate from the northern (southern) null in the nightside. These magnetic field lines form the separatrix between open magnetic field lines of new and old polar caps.

高解像度 M-I 結合シミュレーションによって、テーターオーロラ上空磁場のトポロジー構造を調べた。まず北向きIMFBy-の状態で準定常解を作る。この時に IMF の強度をやや強くする。この条件では、良く知られている、2 ヌル２セパレーター構造が得られる。次に IMFBy ＋にチェンジする。しばらくして、北（南）半球では午前（午後）側のオーバルが高緯度方向に剥がれ、極冠中央方向に移動するようにして、テーターオーロラが再現される。その背後には、新しい極冠が現れる。次に新しい極冠が極冠全体の５分の１程度を占める時の構造を解析する。テーターオーロラが発生している時でも、昼側のセパレーターラインの構造は、By 反転前とそれ程違わない。ただし、ヌル点と stem は、北半球で、午前側から午後側に移行する。北半球の（南半球の）昼側ヌル点を通る磁力線は、南半球の（北半球の）午後側（午前側）にできる新しい極冠の低緯度の縁に繋がる。これに対し、夜側セパレーターラインのトポロジーは、By 反転前と大きく変化する。夜側セパレーターライン上では、尾部に２０ Re 程度入ったところに、新たなヌルが２つできる。これらのヌルは、saddle point bifurcation ヌルの構造を示す。北の（南の）テーターオーロラを通る磁力線は、夜側の北側（南側）ヌルから分岐し電離圏に至る。これらの磁力線は、新旧極冠の open 磁場に対して、separatrix となっている。

グローバルMHDシミュレーションデータを用いたシータオーロラの成長過程の解明

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Evolution process of the theta aurora inferred from the analyses of global MHD simulation data

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The theta aurora sometimes appears in the polar cap region when IMF (Interplanetary Magnetic Field) By polarity reversal under the northward IMF condition. This aurora is thought to be caused by the plasma sheet which penetrates in the lobe region by IMF By polarity reversal.

The magnetic field structure change associated with the theta aurora has not been studied sufficiently yet. The present paper tries to elucidate the structure change by using the global MHD simulation. It is known that the 2-null 2-separator structure is created in the northward IMF condition. This structure is basically established in the superposition of a dipole field of the Earth and a uniform magnetic field of the IMF (Watanabe and Sofko, 2008). We call it null-separator structure.

There are many previous studies about the theta auroras. However, temporal evolutions of plasma processes in the magnetosphere-ionosphere system during the whole life span of the theta aurora activity, that is to say, during the IMF By polarity reversal, have not been studied in detail yet. In order to reveal the plasma processes in the magnetosphere-ionosphere system, we perform MHD simulation by changing IMF By polarity from negative (-4.3nT) to positive (+4.3nT) under the northward IMF condition (Bz=4.3nT). It is also our target to elucidate the magnetic field structure evolution during the IMF By polarity reversal. Simulation results seem to show there are three stages of the theta aurora evolution from the view of plasma disturbances in the magnetosphere. The first stage can be defined as the phase when the plasma convection in the dayside lower altitude magnetosphere changes its direction. The second one is the phase when the bar of the theta aurora (a tongue of enhanced pressure toward the lobe region) appears and becomes gradually smaller. The last stage is the phase where a new plasma tongue is extended from the plasmasheet to the lobe and finally decays. From the viewpoint of the magnetic field structure, it is revealed that the reversal of By polarity causes rapid shift of the null points to the points opposite to the original null point position with respect to the noon meridian. At the same time, the null points corresponding to the old By condition are separated from original null points and shift to the downstream direction of the solar wind. Then, 4-null 4-separator structure is created on the magnetosphere (Tanaka et al. 2010). In this presentation, we will talk mainly about deformation of the magnetic field structure associated with the By reversal and associated transformation of plasma sheet.

IMF(Interplanetary Magnetic Field) の Bz 成分が正、つまり北向きの状況下で、By 成分 (朝夕成分) の符号が反転すると極冠域にアークが出現し、シータオーロラが発生することがある。このアークを発光させているのはプラズマシート由来のプラズマであり、これは IMF の By の符号が反転したことによりプラズマシートがローブ領域に侵入していくことが関係していると考えられている。

シータオーロラ出現時の磁場構造の変化は、まだよく調べられていない。先行研究では、グローバル MHD シミュレーションを用いて磁場構造の変化を明らかにしようとした。また、北向き IMF の状況下では、地球磁気圏は 2null-2separator という構造になることが知られている。この構造は通常、双極子磁場と一様磁場を重ね合わせたときにできる (Watanabe and Sofko, 2008)。これを null-separator 構造と呼ぶ。

シータオーロラについての多くの先行研究があるが、シータオーロラ出現前から消失まで、すなわち IMF By の極性が反転中の磁気圏、電離圏におけるプラズマの時間変化については、まだ詳細には研究されていない。磁気圏-電離圏におけるプラズマの動きを明らかにするために、IMF 北向き（Bz = 4.3nT）の状況下で、IMF By の極性を負（-4.3nT）から正（+4.3nT）に変化させ MHD シミュレーションを実行した。また、IMF By の極性反転時の磁場構造の変化を解明することも目標としている。シミュレーション結果は、磁気圏におけるプラズマ変化の観点から、シータオーロラの成長過程には、前回報告（JPGU,2017）したように、3 つのフェーズが存在することを示している。第 1 フェーズは、昼間の低高度磁気圏でのプラズマ対流がその方向を変えるときの位相と定義することができる。 第 2 フェーズでは、シータオーロラ（ローブ領域に向かってのびる高圧領域）のバーが現れ、徐々に小さくなる。最後のフェーズでは、新たな高圧領域がプラズマシートからローブ領域に伸びて最終的に無くなる。磁場構造の観点から、By の極性の反転は、正午子午線に対して元のヌル点位置と反対側の点にヌル点を急速にシフトさせることが明らかになった。同時に、古い By 条件に対応するヌル点は元のヌル点から分離され、太陽風の下流方向にシフトする。次に、磁気圏上に 4-null-4separator 構造が形成される（Tanaka et al。2010）。今回の発表では、主に By 反転と関連する磁場構造やプラズマシートの変形について述べる。

サブストーム発達過程の太陽風依存性に関するシミュレーション研究

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Simulation study on dependence of substorm evolution on solar wind condition

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A substorm is one of the remarkable disturbances occurring in the magnetosphere. It is known that the substorm is happened frequently when the interplanetary magnetic field (IMF) is southward and solar wind velocity is high. However, the physical process to determine substorm scale is not well understood. We reproduced substorms by using global MHD simulation, found auroral electrojet flowing in the ionosphere and investigated the dependence of substorm evolution on solar wind condition. Solar wind speed 372.4 km/s and northward 5.0 nT IMF was given, we created the stationary state of the magnetosphere. Then the solar wind parameters were changed in step function as follows and substorms were generated. 3 kinds of solar wind speed such as 300 km/s, 500 km/s and 700 km/s and 5 kinds of northward IMF Bz such as -1.0 nT, -3.0 nT, -5.0 nT, -7.0 nT and -9.0 nT were assumed and the total of 15 simulations were performed. In order to objectively evaluate substorms intensity, onset was identified with reference to the method proposed by Newell et al. (2011). This method uses the SME index extends the AE index. In this study, the geomagnetic variation generated by ionospheric Hall current is obtained every 1 degree from the magnetic latitude 40 degrees to 80 degrees and in every 0.5 hours in the magnetic region direction, then the upper and the lower envelope of the geomagnetic variation is regarded as SMU index and SML index, respectively. The larger the solar wind speed, the larger the southward IMF, the more the onset tends to be faster. This tendency is consistent with the onset occurrence probability indicated by Newell et al. (2016). Furthermore, the minimum value of the SML index within 30 minutes from the start of onset tends to decrease as the solar wind speed increased and as the southward IMF was larger. A rapid decrease of the SML index can be explained by a rapid increase of the field-aligned currents flowing in and out of the nightside ionosphere. This means that electromagnetic energies flowing into the ionosphere increase abruptly. The analogy with electric circuit indicates that the ionosphere is a load and dynamo is necessary in the magnetosphere. We will discuss the physical process defines the SML index from the point of energy flow from the solar wind to the ionosphere.

サブストームとは地球磁気圏で発生する顕著な擾乱現象の一つである。サブストームは惑星間空間磁場 (IMF) が南向きでかつ、太陽風速度が大きいときに発生しやすいことが知られている。しかしながら、サブストームの規模を決める物理過程はよく分かっていない。私たちはグローバル MHD シミュレーションを用いてサブストームを再現し、電離圏を流れるジェット電流を求め、太陽風に対する依存性を調査した。太陽風速度 372.4 km/s、北向き 5.0 nT の IMF を与え、磁気圏の定常状態を作成した。その後太陽風パラメータを以下のようにステップ関数的に変え、サブストームを発生させた。仮定した太陽風速度は 300 km/s、500km/s、700km/s の 3 種類、IMF Bz は-1.0nT、-3.0nT、-5.0nT、-7.0nT、-9.0nT の 5 種類で、合計 15 通りである。客観的にサブストームの規模を評価するため、Newell et al. (2011) が提案した手法を参考にオンセットを同定した。この手法は AE 指数を拡張した SME 指数を用いるものである。本研究では SME 指数を磁気緯度 40 度から 80 度まで 1 度ごと、磁気地方時方向に 0.5 時間ごとに電離圏ホール電流が作る磁場変化を求め、上側の包絡線を SMU、下側の包絡線を SML とした。太陽風の速度が大きいほど、南向きの IMF が大きいほど、オンセットが早まる傾向があった。これは Newell et al. (2016) で示されているオンセット発生の確率と調和的である。また、オンセット開始から 30 分以内の SML の最小値は太陽風速度が大きいほど南向きの IMF が大きいほど小さくなる傾向があった。SML 指数の急激な減少は夜側電離圏に流出入する沿磁力線電流の急増で説明できる。これは電離圏に入射する電磁エネルギーの急増を意味するものである。電気回路との類推で電離圏は負荷であるので、磁気圏にダイナモが必要である。本発表では太陽風から電離圏に至るエネルギーの流れと対流の観点で、サブストームの大きさを決める物理過程について議論する予定である。

プラズマ対流に直交する方向に伝搬する沿磁力線加速領域

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Field-aligned auroral acceleration region propagating in the direction perpendicular to the plasma convection

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It has been reported that discrete auroral arcs in the duskside Region 1 current sometimes propagate in the direction perpendicular to the background plasma flows, i.e. in the latitudinal direction, at speed of several km/s. Recent satellite observations have shown that the differential energy flux of particles above the discrete auroral arc is characterized by high energy, several keV electrons, which is known as the inverted-V arc, and there also exist associated upward field-aligned currents and field-aligned potential drops accelerating electrons. In this study we report the initial result from the calculation of the propagating field-aligned acceleration region in the assumed geometry of the duskside Region 1 and the associated magnetosphere. We discuss the importance of the distribution of the enhanced pressure in the limited region of the duskside magnetosphere.

夕方側の Region 1 沿磁力線電流領域において、discrete オーロラアークが、背景のプラズマ流に直交する緯度方向に数 100 m/s から数 km/s の速さで移動する現象が報告されている。また、最近の衛星観測から、この discrete オーロラアークの上方では、数 keV オーダーのエネルギーの電子の降下によって特徴付けられる、いわゆる inverted-V の構造が存在し、それに伴い電離圏から磁気圏へと流れる上向きのメソスケールの沿磁力線電流が生じていることもわかってきた。このようなオーロラ現象は、緯度方向に数 km/s までの移動速度になることを考えると、背景のプラズマ流の緯度がゆっくりと上がったり下がったりするプロセスとは独立であると考えられる。そのような高速の移動を説明するメカニズムはまだ明らかにされていない。

本研究では、夕方側の Region 1 沿磁力線電流領域と、それにつながる磁気圏領域をモデル化することにより、沿磁力線加速領域がプラズマ対流に直交する方向に伝搬する可能性を調べた初期結果を報告する。まず、背景量としての Region 1 電流が定常的に生成されている状況をモデル化した。その領域の特定の場所に、増大した圧力の分布を与えることで、磁気圏対流を局所的に減速させ、それに伴う渦度変化により、背景場の Region 1 電流中にどのようなメソスケールの沿磁力線電流構造が生み出されるのかを求めた。そして、その上向き沿磁力線電流領域と沿磁力線加速領域を関係づけた。圧力の初期分布とその時間変化に関連する各種パラメータを変化させることで、現象を説明するには何か重要であるのかについて考察した結果を報告する。

QZSとMAGDASによる磁気圏FAC－電離圏電流回路の長期間同時観測：統計解析

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Statistical analysis of FAC-ionospheric current circuits simultaneously observed by QZS in space and MAGDAS on the ground

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FACs (Field-Aligned Currents) have been observed by geosynchronous satellites, polar-orbit satellites, ground magnetometers, etc. There are many papers on them. However, there are limited number of papers which reported cases in which an FAC were simultaneously observed by a satellite and a set of ground magnetometers for a long time. We analyze magnetic data from QZS (Quasi-Zenith Satellite) run by JAXA and MAGDAS (MAGnetic Data Acquisition System) run by the International Center for Space Weather and Education (ICSWSE), Kyushu University. QZS has a tilted geostationary orbit, and its footpoint moves but always stays near a set of three ground magnetometers (Kotel'nyy, Tixie, and Chokurdakh) in Siberia. Therefore, it is possible to simultaneously observe FAC-ionospheric current circuits for a long time by using QZS and the Siberian MAGDAS. We intend to study them on a statistical basis, and the results will be presented at the meeting.

磁気圏を流れる沿磁力線電流（Field-Aligned Current; FAC）は、電離圏電流と結合して磁気圏―電離圏間でエネルギーを輸送する。そのため、その結合電流系の理解は磁気圏電離圏連続系の理解において重要である。

これまでに FAC は静止軌道衛星、極軌道衛星、地上磁力計、などによって観測されており多数の報告例がある。しかしながら、同一の FAC を長時間にわたって衛星と地上で同時観測した報告例は少ない。JAXA が運用する準天頂衛星（QZS; Quasi-Zenith Satellite）に搭載されている磁力計と九州大学国際宇宙天気科学・教育センター (ICSWSE; International Center for Space Weather Science and Education) が中心となって運用する地磁気観測ネットワーク MAGDAS (MAGnetic Data Acquisition System) を用いると、下記の通り、同一 FAC の長時間同時観測が可能である。

QZS は静止軌道に軌道傾斜角 40 度と軌道離心率 0.1 を持たせた軌道をとるため、QZS の footpoint はシベリア付近に長時間滞在する。そのため、QZS とシベリアの MAGDAS 観測点を使って同一 FAC を長時間同時観測することが可能である。

本研究のもう一つの利点は、QZS は磁気圏高緯度領域に長時間滞在することができる点である。そのため、これまで報告例の少ない静止軌道高度 PSBL(Plasma Sheet Boundary Layer) を流れる FAC を長時間観測できる。

本講演では、2010/10/1～2013/3/31 の期間における QZS と MAGDAS による同一 FAC の長時間同時観測についての統計解析の結果について報告する。また、同時観測例の中には FAC と結合した電離圏電流を MAGDAS が観測したイベントも存在している。それについても報告する。

Stream function of global ionospheric plasma velocity distributions estimated from SuperDARN data

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Dynamics of ions in the inner-magnetosphere are highly controlled by electric field in the magnetosphere-ionosphere system. The SuperDARN provides valuable information on the ionospheric plasma drift velocity distribution which can readily be converted into the electric field distribution. However, there are some wide gaps in the spatial coverage of the SuperDARN, although the field of SuperDARN has been gradually expanding by the deployment of new radars. In addition, each radar give only the line-of-sight component of drift velocity and the data are frequently missing. We propose a new approach for estimating the global distribution of drift velocity by combining an empirical global model and the SuperDARN data. The gaps in the spatial coverage of the SuperDARN are filled with the empirical model. In addition, the divergence free condition is used as a constraint for the estimation. If plasma drift velocity is assumed to be divergence-free, we can consider a stream function yielding the plasma velocity distribution. We express the stream function by a linear combination of kernel functions, and obtain the drift velocity distribution by estimating this stream function from the SuperDARN data. We will demonstrate a preliminary results obtained by our proposed method.

Ap∗指数とDst指数で見た地磁気嵐

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Geomagnetic storm in Dst and Ap∗indices

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Dst and Ap∗indices were compared as indicators of geomagnetic storm. They are estimated from geomagnetic data of the observatories in the different latitudinal zone. Therefore, it is expected that these two indices show different behavior in the storm time. In this presentation, time variation of these indices in some storm time and discussed the problem of the determination of the storm period.

地磁気嵐の発達の目安としてはDst指数がよく用いられるが、一方Kp指数を元に作られるAp∗指数も特に磁気嵐の期間を定めるのに用いられる。しかしながらDst指数とAp∗指数 (或いは大元であるKp指数) とでは算出法だけでなく用いられている観測所の緯度帯や導出法が違うので、それぞれで見た地磁気嵐の期間や特性も異なると予想される。

本発表では、いくつかの地磁気嵐についてDst指数とAp∗指数さらにその元になるap指数の時間変化とその違いを調べ、地磁気嵐の期間をAp∗指数で決めることの妥当性を議論する。

全天大気光イメージャとSwarm衛星を用いた極冠オーロラ近傍の電流系に関する研究

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Observation of current system in the vicinity of polar cap aurora by all-sky imager and Swarm

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Polar cap aurora is a class of discrete aurora that is sometimes observed in the polar cap region when the interplanetary magnetic field (IMF) is directed northward. Polar cap auroras are further divided into several types. One is poleward moving polar cap aurora (PMPCA), which move poleward periodically in the morning side. The other is sun-aligned arcs (SAA), which are mostly directed towards the Sun and move in the dawn-dusk direction in close association with IMF By. Although these polar cap auroras are expected to have different generation mechanisms and source regions, details are not yet clarified. To discuss these unresolved problems, it is necessary to elucidate the M-I coupling process above polar cap auroras.

One possible approach to understanding the M-I coupling in the vicinity of aurora is to examine the spatial structure of field-aligned currents (FAC). Within auroral arcs, the energetic electrons precipitate from the magnetosphere into the ionosphere along the magnetic field line and FAC flows from the ionosphere to the magnetosphere. By measuring FAC, it is possible to understand the M-I coupling process above polar cap auroras. In the past, FAC was derived indirectly from the temporal variations of the magnetic field measured by the low-altitude satellites such as DMSP and CHAMP. However, since these observations are single satellite measurement, it was necessary to assume that the structure of aurora does not change during the overpass of the satellite.

To resolve this problem, in this study, we make use of the magnetic field from the Swarm satellites. Swarm consists of three satellites Swarm A, Swarm B, and Swarm C, and it observes magnetic field at three points at the same time at a temporal resolution of 50 Hz. Swarm A and C are flying roughly along the same orbit at an altitude of about 460 km. By combining these two satellites, it is possible to calculate the FAC density without assuming temporal variations as spatial variations. In this study, by combining data from Swarm and an all-sky air glow imager of (OMTIs) at Resolute Bay in Canada, we investigate the relationship between polar cap aurora and FAC. In particular, we examine FAC derived from single and dual satellite methods during a simultaneous observations of polar cap aurora on February 28, 2016.

During the interval of interest, a SAA type polar cap aurora was observed over Resolute Bay from 0500 UT to 0700 UT. The poleward part of the arc was split into two parts. Swarm A and C passed the structure along the direction almost parallel to the arc at 0617 UT. The satellites also crossed one of the splitted arcs at 0616 UT. During the interval of the crossings, we derived 1) FAC density from Swarm A, 2) FAC density from Swarm C, and 3) FAC density from A and C through the dual satellite method. Regarding the FAC densities derived from the single satellite method, the relationship between the crossing of the optical arc and enhancement of upward FAC is unclear. On the other hand, FAC derived from the dual satellite method shows a good agreement with the optical intensity variation along the satellite track. This difference may be due to the fact that the track of the satellites was almost parallel to the arc and it was difficult to observe magnetic field changes across the arc. In contrast, for the FAC derived by the dual satellite method, Swarm A and C sandwiched the arc, which is a favorable situation for the calculation of FAC. In the presentation, we will report other examples of simultaneous observations of polar cap auroras, especially rapidly moving PMPCA type and discuss the validity of using FAC derived from the dual satellite method.

極冠オーロラは、Interplanetary magnetic field (IMF) が北向きのときに磁気緯度約 75 度 以上の極冠域で頻繁に観測されるオーロラ現象である。極冠オーロラはいくつかのタイプに区分され、複数のアークが極方向に間欠的に移動する時間変化の激しい Poleward Moving Polar Cap Arcs (PMPCA) や、孤立した状態で太陽方向に伸びた構造をしている比較的時間変動の少ない Sun-Aligned Arc (SAA) などが知られている。これらの極冠オーロラはそれぞれ異なる発生メカニズムやソース領域を持つと考えられているが、詳細は明らかになっていない。発生メカニズムやソース領域を同定するためには、磁力線を介した磁気圏と電離圏のカップリング (M-I Coupling) を理解する必要がある。

オーロラの近傍の M-I Coupling を理解するためのひとつのアプローチとして Field-Aligned Current (FAC) を解析する手法がある。オーロラの発光領域では、オーロラの光らせる電子が磁力線に沿って磁気圏から電離圏へ降下しており、それに伴って電子の運動と反対方向の電離圏から磁気圏方向へ上向きの FAC が発生していると考えられている。この FAC を測定することでオーロラ近傍の M-I Coupling の時空間変動に関する情報を得ることができる。過去の研究では DMSP や CHAMP などの衛星による磁場観測の時間変化から FAC の導出が行われてきた。しかし、これらの衛星は単機観測であるため、時間変化から磁場の回転を計算する際にオーロラの空間構造が時間的に変わらないということを前提とする必要があった。

本研究では、この問題点を克服するために地磁気観測衛星 Swarm による編隊飛行観測を用いて、極冠オーロラ上空の FAC の導出を行う。Swarm は A, B, C の 3 機による編隊飛行をしており、0.5 nT の分解能で同一時刻に 3 地点で 50 Hz

の磁場観測を行っている。このうち A と C は高度約 460 km をほぼ同一軌道で飛行している。そのため、数 10 km の空間幅で 2 地点における観測を行い、 2 点間の磁場の空間変化から時間的な不変性を仮定することなく FAC を算出することが可能である。本研究では、Swarm による磁場観測とカナダ・レゾリュートベイに設置されている全天大気光イメージャ Optical Mesophere Theremosphere Imagers-: OMTIs による同時観測事例について、単機観測と複数機観測のそれぞれによって求められた FAC と極冠オーロラの関係を考察する。

2016 年 2 月 28 日の同時観測事例では、0500 - 0700 UT にかけてレゾリュートベイで発光強度 500 R 弱の SAA 型の大規模な極冠オーロラが観測された。IMF By は正の値をとっており、ゆっくり夕方方向へ移動していた。また、極側の領域でアークは 2 本に分岐しており、split-transpolar aurora (split-TPA) の特徴も見られた。この極冠オーロラを Swarm A と C は 0617 UT 頃アークに対してやや平行気味に通過した。また、 0616 UT 過ぎには分岐したアークの夕方側のアークも通過していた。この時間帯に観測された磁場から、1) A による単機観測に基づいた FAC 密度、2) C による単機観測に基づいた FAC 密度、3) A, C の 2 機観測に基づいた FAC をそれぞれ求めた。単機による観測では、C についてはアークの通過時刻と上向き FAC のピーク時刻が一致しているように見られたが、A については明確な対応関係が見られなかった。一方、2 機観測によって求められた FAC ではオーロラの発光と上向き FAC の明らかな対応が見られた。この違いは、衛星がアークに対して平行に近い軌道を通ったために、軌道に沿った方向の磁場に急激な変化が現れにくく、一方、2 機観測では A と C がアークを挟むように位置しているので磁場の空間変化を観測しやすい状況であったためであると考えらえる。本事例では対象オーロラが動きの遅い SAA であったが、 2 機観測による時間変化を含まない FAC 観測の有用性を確認するためには、 PMPCA などの動きの激しい事例の解析も必要であると考えられる。

ＭＭＳ衛星を使った衝撃波前面のホイッスラー波観測

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Shock-upstream whistler waves observed by MMS spacecraft

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With the advent of the MMS mission, it has become possible to study electron-scale plasma phenomena in situ in space, a logical extension of what has been done using the Cluster mission on the ion-scale physics. Here I show two MMS events of electron-scale whistlers in the shock-upstream region, ahead of Earth's bow shock. Using the magnetometer data and the wave telescope projection method, the magnetic fluctuation energy is determined not only as a function of the frequencies but also as a function of the three-dimensional wavevectors. The wave dispersion relation can then directly be compared between the observations and the wave or instability theories. One case is a foreshock wave event, upstream of the quasi-parallel shock Whistlers propagate nearly along the magnetic field. The other case is a shock-foot event, upstream of the quasi-perpendicular shock, and here again, whistlers are observed that propagate obliquely to the mean magnetic field. An important lesson is that the whisler waves are excited ahead of the shock wave regardless the geomertry or angle of the upstream magnetic field to the shock normal direction. Excitation of the whistlers is an important channel of the energy dissipation of the collisionless shocks.

MMS 衛星の到来により、宇宙空間プラズマの現象の理解に向けて、従来のクラスター衛星を使ったイオンスケールの物理だけでなく、電子スケールでの物理も直接解明できるようになってきた。MMS 衛星の衝撃波（地球前面のバウショック）観測２例から、衝撃波前面でホイッスラー波が励起されている現象を紹介する。解析は、MMS 衛星の磁場データと wave telescope（波動望遠鏡）射影法を使って、周波数と３次元の波数空間で磁場のゆらぎのエネルギー分布を測定し、エネルギーの極大値（ピーク値）での周波数と波数ベクトルを見つける作業をする。解析作業の結果、プラズマの平均流に乗ったプラズマ静止系での分散関係が観測から得られ、周波数と波長ともにイオンと電子のスケールの中間にあたるスケールで波の分散関係をプラズマ理論のものと直接比較をすることが可能になる。観測結果は、（１）準平行衝撃波前面のフォアショック領域では磁場方向に平行伝搬するホイッスラー波動が見つかり、（２）準垂直衝撃波前面の遷移域（フット領域）では磁場方向に斜め伝搬するホイッスラー波動が見つかった。具体的な励起機構はさまざまであるが、磁場と衝撃波のなす角度に関わらずホイッスラー波が衝撃波前面で励起されていることが分かる。すなわち、衝撃波の散逸機構およびエネルギー分配先としてホイッスラー波動は大事な役割を果たしている。

Adjustment of the offset level for the simplified magnetometer using MI sensor

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Geomagnetic observation to understand plasma dynamics in the magnetosphere has been conducted by many investigators from the nineteenth century. In order to observe the magnetic perturbation with the accuracy of ˜0.1 nT, the fluxgate magnetometer has been usually installed in many artificial satellite as well as on the ground observations.

Kanno and Mori (1997) suggested that a permeability of an amorphous wire varies with the intensity the ambient magnetic field strength. This causes a linear proportional relationship between a skin-depth of the RF current in the wire and an ambient magnetic field. The magnetic sensor by using this basis was produced as the MI (Magneto-Impedance) sensor.

In this study we attempt to apply the MI sensor to an actual magnetometer for the geomagnetic observation. In order to use the MI sensor in the actual geomagnetic observation, it is required to modify the electronic circuit such as the removal of the AC coupling to measure the DC field. The dynamic range of output voltage is from 0 to 5 V which corresponds to +/- 4000 nT of the magnetic variations. However, the output voltage for the total magnetic field intensity could not be calibrated so that the output voltage often saturates with the large geomagnetic field. We develop a sensor case with the solenoidal coil to adjust the offset level, and installed the prototype magnetometer at Sasaguri test field in March, 2017. The measured data obtained in this test observation shows the strong temperature dependence of the MI sensor although the offset level of the magnetic field could be well adjusted. These results indicated that we need more reasonable contraption to compensate the temperature dependence of the MI sensor.

FPGAを用いた汎用スペクトル演算モジュールの開発

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Development of a general-purpose FPGA module for spectrum analyses

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Plasma wave observation has been carried out using scientific satellites to study various kinds of plasma wave propagating in the Earth's magnetosphere. Because the amount of waveform data measured by wave receiver is enormous compared to the telemetry capacity, it is necessary to perform onboard signal processing for the purpose of data reduction to realize efficient data transmission to the ground stations. Signal processing on FPGA (Field Programmable Gate Array) is one of such solutions under the conditions of low power consumption and high speed processing.

We have developed a FPGA module for the data production of spectral matrix that is useful for direction finding of the plasma waves. In the previous trial, however, we utilize IP (Intellectual Property), which is a designed circuit block provided by FPGA vendor. Such vendor-dependent IP is useful for the efficient development of the design and evaluation of the modules, but it cannot be applied to the FPGAs made by the other vendors. In addition, because the internal structure is a black box, it is impossible to apply it for space use. For this reason, we developed a non-IP dependent FPGA module having a same function in the present study. A spectral matrix is derived from cross correlation matrix of 6 components of electromagnetic waveforms. We developed a FPGA module that consists of only non-IP modules and an averaging process of spectral matrices. Finally, we evaluated the performance and found that the developed modules are satisfactory with operation, consumption of resources, and processing time. In the presentation, we report the configuration of the design and the results of evaluation of the production process of spectral matrix we developed.

地球磁気圏内にはさまざまなプラズマ波動が伝搬しており、地球磁気圏を飛翔する科学衛星による波動観測が行われている。一般的に、波動観測では、波形、スペクトル、伝搬方向推定のためのスペクトルマトリクスが観測される。しかし、科学衛星が搭載する波動観測器によって生成される電磁場波形データの量は、衛星が地上に伝送可能な容量に比べて膨大である。したがって、地上へ効率的にデータを送信するために、機上で信号処理を行いデータ量を削減している。機上での信号処理には、低消費電力や高速処理を可能にするために、処理の一部を FPGA(Field Programmable Gate Array) 上に実装することが検討されている。

我々の研究グループでは、宇宙機への適用を目的とした波動観測器用のスペクトルマトリクス演算 FPGA モジュールを開発中である。しかし、先行研究で開発したモジュールの一部には、 FPGA ベンダーが提供する回路ブロックである IP(Intellectual Property) が使用されていた。ベンダーに依存する IP の使用はモジュール設計・評価の効率化に有用であるが、他ベンダー製の FPGA では使用できず、また、その内部構造はブラックボックスであるため、宇宙仕様の FPGA を選定するうえでの障害となる。このため、本研究では同等の機能を持つ非 IP 依存の FPGA モジュールの開発を行った。また、スペクトルマトリクスは、電磁場 6 成分の相互相関行列を計算し平均を求めることで計算されるが、先行研究ではマトリクスの平均処理が未実装であったため、この処理を追加した。最後に開発したモジュールについて、動作や消費リソース、処理時間について評価を行い、いずれも問題ないことを確認した。本発表では、スペクトルマトリクス演算モジュールの構成と性能評価について報告を行う。

将来オーロラ観測ロケットならびに小型衛星搭載可視・紫外イメージャーの開発

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Development of auroral visible and ultra-violet imagers for future sounding rocket and small satellite missions

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http://pparc.gp.tohoku.ac.jp/

We report feasible design of compact-sized optical system for imaging and spectrometer in future space and rocket missions. In particular, we focus on the auroral rocket project G-CHASER which will be launched from Andoya, Norway in January 2019. Recent progress in imaging and spectroscopy in the ultra-violet and visible ranges enable us to study detailed mechanisms of auroral acceleration process as well as wave-particle interaction in geospace. We are now discussing possibilities of next-generation satellites which will measure auroral and thermospheric phenomena, and also plan to carry out rocket experiments for pulsating aurora (PsA). In this presentation, we will give scientific issues to be solved in the auroral and thermospheric studies, and the most recent status of space-based missions.

We propose a visible auroral camera for G-CHASER rocket in addition to medium and high-energy particle detectors. In this rocket mission, we particularly concern on PsA phenomena to understand the loss of the Earth's radiation belts due to precipitation of high-energy magnetospheric electrons through the wave-particle interaction. We will observe the optical thickness of pulsating aurora and the time-dispersed curve in electron energy spectra using the high-time resolution simultaneous optical and particle data. The data is useful to imply the impact of high-energy electrons on the Earth's atmosphere, in particular, the possible change of ion chemistry including ozone (O3) due to precipitation of MeV electrons during PsA. We have started designing of auroral imaging camera (AIC) for this rocket mission. AIC mainly consists of optical objective lens, CCD and electronics. We use a commercial-based fast lens with a wide field-of-view (FOV) of 90 (azimuthal) x 180 (vertical) deg. We adopt a Watec WAT-910HX as a CCD detector. This is a half inch (6.45 x 4.84 cm) CCD with pixels of 768 x 494, and the binning of 384 x 30 pixels is made by the electronics to have a 2 x 16 bin image. The electronics also provide appropriate power supplies for the CCD, FPGA to control the CCD exposure timing, and data production for common electronics of the rocket system that is transferred to the ground. The candidate of target auroral emission is the O2 A-band at 762 nm, and/or N2 emission. We will complete the detailed design within this year and fabricate in early 2018.

In addition we are now discussing on the possibilities for future small- and micro-scale satellites to understand the small-scale aurora and the coupling system between magnetosphere and ionosphere. We carried out the conceptual design of auroral camera assuming that the satellite is three axis stabilized and its apogee is 3000 km. For the visible imager, the target is auroral N2 1P emission at 670 nm and/or O2 A-band emission. The focal lens of objective lens is 100mm with Fno of 1.5, and the preferred detector is 1k x 1k EMCCD with pixels of 1024 x 1024 of which each pixel size is 13 x 13 um. Then, the FOV is 7.6 x 7.6 deg, which enable us to cover 400 x 400 km and 200 x 200 km with spatial resolution of 2 km/bin and 1km/bin (assuming 5-pix binning) viewed from altitudes of 3000 km and 1500 km, respectively. For the ultra-violet imager, we discussed the feasible FOV size viewed from 3000 km altitudes, and considered that the FOV in the range from 34 x 34 deg (1800 x 1800 km at the ionosphere) to 51 x 51 deg (2700 x 2700 km at the ionosphere) is preferable. We designed the wide and fast objective system by using Aplanat mirrors (FOV=40 x 48 deg, Fno=2.4). The candidate of target auroral emission is the N2 LBH band at 140-160 nm. We also concern the feasibility of 2D detector among CCD, CMOS and IICMOS, mirror coating to improve reflectivity and filter to block the H-Ly alpha of geocoronal emission at 122 nm.

SS-520-3/LFAS 搭載用デジタル処理部の FPGA モジュールの開発と評価

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Development and evaluation of FPGA modules for digital processing part in the SS-520-3/LFAS

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The rocket SS-520-3 experiment will be performed in winter, 2017 to study acceleration and heating mechanism of heavy ions in the cusp region. We are responsible for the development of the digital data processing part of WFC (Waveform Capture) in LFAS (Low Frequency Analyzer System) mounted in the SS-520-3 rocket.

LFAS contains two pairs of dipole antenna, and two receivers named EFD (Electric Field Detector) and WFC. The WFC measures electric field in the VLF range below 10 kHz and generate digital data which consist of one channel of spectrum and two channels of waveform. It is necessary to sample waveform with accurate timing to study energy exchange process between plasma waves and plasma particles via wave particle interaction directly and quantitatively by SWPIA (Software-type Wave Particle Interaction Analyzer).

Three FPGAs will be installed in the LFAS. One FPGA is supplied to the WFC digital part and the others are used for a common digital part of LFAS. In the PWA (Plasma Wave Analyzer) mounted in the SS-520-2 rocket experiments, the data flow was quite complicated between the DSP and the CPU to process the telemetry data using waveform compression and FFT. However, in the WFC digital part mounted in the SS-520-3, these processes are executed in parallel on the FPGA and functions are integrated on one chip, that achieved drastic speed up of data processing and reduction of the board size. In addition, as a counter to secure the synchronousness between waveforms and particles, SWPIA counter is generated in the FPGA. In the waveform compression module, subband compression is carried out every 1,024 points. In the spectrum generation module one set of 512 points of FFT followed by two combinations of 1/8 decimation and 512 points of FFT are performed in parallel, and the logarithm amplitude is finally calculated. It observes spectrums of three frequency bands, that is, 1 kHz - 10 kHz, 100 Hz - 1 kHz and below 100 Hz. Both the compressed waveform and spectrum data are transmitted to another FPGA which is responsible for a common digital part of LFAS. It performs telemetry transmission processing afterwards. The data output from the WFC digital is 8 bits parallel and 4 bits of status data are additionally transmitted for the purpose of data identification. Furthermore, a data latch clock is provided from the WFC digital to the common digital part for the data reception.

We have already developed FPGA modules of waveform compression as well as spectrum processing, and they work fast enough to process the data within real-time. We also confirmed that the total amount of generation data is within telemetry transmission capacity. Specifications for the controller of AD converter, the packet generation unit, and the interface among peripheral circuits were fixed, and the development was completed. Finally, environment tests such as vacuum test and vibration test of LFAS have been safely completed.

In the presentation, we report further detailed signal processing section of the developed WFC digital part, the I/F among peripheral circuits and evaluation results of the performance tests.

極域カスプ領域における重イオンの加速・加熱の解明を目的として, 2017 年度冬に SS-520-3 号機による北欧ロケット実験が予定されている. 本研究ではこの SS-520-3 観測ロケット搭載の低周波波動解析システム (Low Frequency Analyzer System : LFAS) 内の波形捕捉受信器 (Waveform Capture : WFC) のデジタル部の開発を行う.

ここで, LFAS は 2 組のダイポールアンテナと電場観測器 (Electric Field Detector : EFD), WFC の 2 種類の受信器を搭載している. WFC では電場 2 成分 (CH1, CH2) の 10 kHz 以下の低周波信号を計測し, 地上へは 1 チャネルのスペクトルデータと圧縮処理を施した 2 チャンネルの波形データを伝送する. さらにこのロケット実験では「ソフトウェア型波動粒子相互作用解析装置 (Software-type Wave Particle Interaction Analyzer : SWPIA)」により, 取得したデータから波動粒子相互作用によるプラズマ粒子とプラズマ波動間のエネルギー交換過程を直接かつ定量的な解析が計画されており, データの正確な取得タイミングを保証する必要がある.

WFC デジタル部は単体の FPGA で構成される. 以前のロケット実験に用いられた SS-520-2 号機に搭載されたプラズマ受信機 (Plasma Wave Analyzer : PWA) では DSP 及び CPU を併用した複雑なデータフローで波形圧縮, FFT などを実現していた. しかし, 今回の SS-520-3 号機に搭載する WFC デジタル部ではそれらの処理を FPGA 上で並列動作させ, 波形データの圧縮処理とスペクトル観測機能を 1 チップに集約することで処理の高速化・専有面積の縮小を図る. また, 波形と粒子の同期性を確保するためのカウンタとして, SWPIA カウンタを FPGA 内部で生成し出力データに付加する. 波形処理部では, 信号を複数の周波数帯域に分割し, 分割された各帯域での信号強度の違いを利用し, ビット長を削減する圧縮手法であるサブバンド圧縮を 1,024 点ごとに行う. スペクトル処理部では, 1/8 デシメーションと 512 点 FFT を行い, 最終的に対数振幅を算出して 1 kHz - 10 kHz, 100 Hz - 1 kHz, 100 Hz 以下の 3 つの帯域を観測する. その後, 処理を施したデータ

から地上でデータを解析可能にするためにパケットを生成し, 後段のテレメトリ送信処理を行う FPGA に送信する. WFC デジタル部からのデータ出力は 8 bits のパラレルであり, 加えてデータの識別用に 4 bits のステータス信号を出力する. さらに, 後段の FPGA が送信データを受け取れるようにデータラッチ用クロックを WFC デジタル側から送信する.

現状では, 波形の圧縮処理及び, スペクトルの生成処理ともにリアルタイムで処理できることが検証済みで, 所定のテレメトリ伝送容量内にデータを収めることにも成功した. また, AD コンバータのコントローラやパケット生成部, 周辺回路との I/F について最終的な仕様が決定し, 開発が完了している. さらに, LFAS 全体として真空試験, 振動試験などの試験が完了している.

本発表では完成した WFC デジタル部の詳細な信号処理部, 周辺回路との I/F, 観測シーケンス, 環境試験で取得した動作結果とデータの評価結果について説明する.

SS-520-3号機によるカスプ領域のプラズマ粒子観測

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SS-520-3 Observation of Plasma Particles in the Cusp Region

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In the terrestrial magnetosphere, plasma particles with a wide energy range from < 1eV to MeV exist simultaneously. These particles are generated and/or transported via interactions with plasma waves. These ions in the cusp region are often observed to be accelerated, heated and flowing out of the magnetosphere. However, acceleration and transport processes of these particles are still unknown.

We will launch SS-520-3 sounding rocket from Svalbard in order to understand the acceleration mechanism of escaping ions from ionosphere in the cusp region. SS-520-3 will be launched near the winter new moon in 2017 targeting the dayside cusp region aiming to reach over 800 km. In this experiment, EISCAT radar observation from the ground and optical observation will be simultaneously made.

In this rocket, "Low-energy ion instruments: LEP - EISAi", "Low-energy electron instruments: LEP - EISAe", "Low-energy ion mass analyzer: IMS" and "Thermal and supra-thermal ion analyzer: TSA" are onboard in order to observe low energy (1eV/q ˜several keV/q) plasma particles escaping from ionosphere.
LEP is a top-hat type electrostatic analyzer, which can measure both ions and electrons by switching the polarity of the high voltage applied to the analyzer.
TSA and IMS are energy mass spectrometer combining a top hat type electrostatic and a time of flight mass spectrometer. SS-520-3 will be the first opportunity to flight verify TSA's functions such as an extension from rocket/satellite body and a control of analyzer potential that is quite important in the future thermal and supra-thermal ion observation by spacecraft.
We will also try to decide the energy flow between plasma waves and plasma particles by conducting direct observation of wave particle interaction using TSA-IMS and low frequency wave analysis system (LFAS) as Wave-Particle Interaction Analzer (WPIA). The heating and acceleration mechanism of the particles by the wave which leads to the outflow of the ionized atmosphere particles will be studied from the in-situ data obtained by this experiment.

In this presentation, we will show the outline and the test results of the plasma particle sensors as well as the current progress in the preparation of the rocket flight.

地球磁気圏には数 eV 程度の熱的・超熱的と呼ばれる低エネルギー粒子から数 MeV を超える高エネルギー粒子まで、幅広いエネルギー帯のプラズマ粒子が同時に存在している。これらの粒子は地球磁場や太陽風プラズマなどと電磁場を介して相互作用し、加速や輸送を経て生成・消滅することで多様なプラズマ環境を形成している。
これらプラズマ中のイオンは極域上空のカスプ領域において、しばしば磁気圏外部に向かって加速、加熱され、流出していることが観測されている。しかしこの加速機構については、波動粒子相互作用の影響などの説があるものの、いまだ解明されていない。

これらカスプ上空電離圏最上部における流出イオンの加速メカニズム解明を目的として、ノルウェー・スバルバール諸島から観測ロケット SS-520-3 号機を 2017 年度冬季新月付近に打ち上げる予定である。観測領域として極域昼間側のカスプ領域上空を設定し、到達高度は 800 km 以上を目標としている。本実験では観測ロケットによるその場観測と同時に地上からの EISCAT RADAR 観測や光学観測も予定されている。

本ロケットには、電離圏から流出する 1eV/q˜数 keV/q 程度の低エネルギープラズマ粒子を観測するための機器として「低エネルギーイオン観測装置：LEP-EISAi」、「低エネルギー電子観測装置：LEP-EISAe」「低エネルギーイオン質量分析器：IMS」「熱的イオン観測装置：TSA」の 4 つの観測機器が搭載される。
低エネルギー荷電粒子観測装置：LEP はトップハット型の静電分析器であり、高電圧電源の極性を交互に切り替えることでイオンと電子の両方を測定できるようになっている。
熱的イオン観測装置：TSA、低エネルギーイオン質量分析器：IMS はトップハット型の静電分析器と飛行時間質量分析器を連結した機器であり、特に TSA は飛翔体からの伸展や筐体電位の制御など今後の熱的・超熱的イオン観測に必要な技術の実証実験も兼ねている。
またこれらの粒子計測器とともに搭載される低周波波動解析システム LFAS と TSA/IMS のデータを精密な時刻データとともに機上のメモリーに保存した上で地上に送り、同時に解析することで、波動粒子相互作用における波動と粒子の間のエネルギー授受の直接観測を行う予定である。これにより、これまで十分な理解が得られてこなかった電離大気の流出に繋がる、波動による粒子の加熱・加速メカニズムをその場観測のデータにより研究できるようになる。

現在ロケットは打上げに向けた最終調整を行っているところである。
本発表では、ロケットに搭載されるセンサの概要と試験結果、さらに現在の進捗状況について述べる。

SS-520-3号機観測ロケットによる昼側カスプ領域のDC電場観測計画

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DC electric field observation project in dayside cusp region by SS-520-3 sounding rocket

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From past rocket experiments it has been observed that heating and acceleration of ions occurs in the cusp region. It is a boundary region between open magnetic force lines toward the night side and a closed magnetic force lines toward the day side. It is known from the observation results so far that a large amount of ion is flowing out from the polar. In order for heavy ions supposed to be bound by the earth's gravity to flow out of the upper atmosphere, some kind of acceleration and heating phenomenon must be working. However, it's physical phenomenon has not been elucidated. We launch the rocket equipped with each instrument toward the cusp region in order to observe the physical quantity for the investigation of the ion acceleration and heating phenomenon in plan of SS-520-3 sounding rocket project in the winter of 2017. In this project, we also analyze the DC electric field, which is thought to be directly involved in ion acceleration and heating phenomena. The electric field detector (EFD) mounted on the rocket uses a 5 m antenna on two by two on diagonally line and used as two sets of 10 m dipole antennas. Therefore, it is possible to perform accurate electric field observation and obtain detailed DC electric field data. Then, using the observation data of EFD, electric field vectors are derived to show the electric field structure in the cusp region, and we are planning to investigate whether the electric field is affecting the ion acceleration and heating phenomenon.

過去のロケット実験からカスプ領域ではイオンの加熱・加速が起きていることが観測されている。カスプ領域とは夜側に向かう開いた磁力線と昼側に向かう閉じた磁力線の境界領域である。これまでの観測結果から大量のイオンが極地から流出していることが分かっているが、地球の重力に縛られているはずの重イオンが上層大気から流出するためには何らかの加速・加熱現象がはたらいていなければならない。しかし、その物理現象は解明されていない。そこで、2017年の冬季に打ち上げ予定のSS-520-3号機観測ロケット実験では、観測機器を搭載したロケットをカスプ領域に向けて打ち上げ、イオンの加速加熱現象のメカニズムを解明することを目的としている。本研究ではその中でもイオンの加速・加熱現象に直接関与していると考えられているDC電場の解析を行う。ここでロケットに搭載される電場観測装置 (EFD) は，センサとして片側5mのアンテナを対角線上に配置し、2組の10mダイポールアンテナとして使用する。そのため精度の良い電場観測を行うことができ、詳細なDC電場データを得ることができる。そして、EFDの観測データを用いて、電場ベクトルの導出を行い、カスプ領域中の電場構造を示し、イオンの加速加熱現象に電場が影響しているか調査する予定である。