

脈動オーロラ降下電子スペクトルの全体像:PARM ロケット実験に向けて

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Simulation of full energy spectrum of pulsating aurora electrons: Implication for the PARM sounding rocket experiment

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Pulsating aurora is caused by intermittent precipitations of a few – tens keV electrons from the plasma sheet. These precipitations are caused by the pitch angle scattering with whistler mode chorus waves. We have proposed a model on precipitations for wide energy electrons from a few keV to more than MeV [Miyoshi et al., 2010, 2015a, Saito et al., 2012]. If the chorus waves propagate to the higher magnetic latitude along the magnetic field line, the resonance energy becomes high enough to cause precipitations of MeV electrons. Several observations have supported this model; sub-relativistic and relativistic electrons simultaneously precipitate into the atmosphere associate with the pulsating aurora. In order to investigate detail of energy spectrum of pulsating aurora electrons, we conduct a simulation on the wave-particle interactions between chorus waves and bounced-electrons along the field line. The simulation result shows that the lower-band chorus waves can cause wide energy electron precipitations from a few keV to more than MeV. At the low-altitude, we observe elements of precipitating electrons with the energy dispersion in the energy-time diagram. The consecutive rising tone elements cause both the internal modulations of precipitating electron flux around 10s keV and the individual bursts at sub-relativistic and relativistic energy range, i.e., microbursts of energetic electrons. The results indicate that the internal modulations of the pulsating aurora electrons and microbursts of sub-relativistic/relativistic electrons are same origin through the wave-particle interactions with the chorus waves. This possibility will be confirmed by the PARM observations onboard the sounding rocket experiments RocSAT-XN (Andoya, Norway) in January 2019 and LAMP (Poker Flat Research Range, Alaska, US) in January 2020.

脈動オーロラ観測ロケットミッション PARM に向けた中間エネルギー電子観測器の開発

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Development of the Medium-energy Electron Detector for the PARM Rocket Mission

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In the Earth's magnetosphere, relativistic-energy ($< \text{MeV}$) electrons are trapped in the region called radiation belt. It is well known that these high-energy electrons rapidly drop out during the geomagnetic storm main phase, but the physical mechanism to be responsible is not exactly known. Although several hypotheses are proposed, they have not been well quantified. Therefore, it is unclear which is the major cause of the loss of the radiation belt electrons. One candidate is the electron precipitation by pitch angle scattering via cyclotron resonance with whistler mode chorus waves. In order to evaluate this mechanism quantitatively, the amount of precipitating high energy electrons should be measured. Nevertheless, in the magnetosphere, where the scattering occurs, it is difficult to identify precipitating electrons because of the small size of the loss cone. On the other hand, in the ionosphere, where the precipitating electrons can be directly measured, it is not easy to identify chorus waves that correspond to the precipitating electrons, since chorus waves do not propagate in exactly parallel to the geomagnetic field, and not always reach the ionosphere with the sufficient intensity). The Pulsating AuroRa and Microbursts (PARM) mission proposes another method, to observe the pulsating aurora (PsA) in the ionosphere instead of the chorus waves, since this type of aurora is driven by chorus wave in the magnetospheric equator. Based on this idea, the PARM mission delivers particle and field instruments for RockSat-XN, a sounding rocket in US to be launched from Andoya, Norway, in January 2019. The four instruments are high energy electron detector (HEP), medium energy electron detector (MED), aurora imaging camera (AIC) and asic-onboard flux gate magnetometer (AFG). We developed MED, which measures electrons with energies from 20 to 100 keV. We first evaluated performances of electronics boards in the unit level, then assembled the sensor, and finally verified integrated performances such as low noise level ($< 3\text{keV}$) and sufficient attenuation of the incident sunlight. MED passed environment tests without any problems, and now it is mounted on the RockSat-XN's deck.

地球周辺の宇宙空間には放射線帯と呼ばれる高エネルギー電子が捕捉された領域が存在する。この高エネルギー電子は磁気嵐と呼ばれる大規模擾乱が起こると急激に減少することが知られているが、その消失機構は未解明である。電子消失の原因の一つとしては電子がホイッスラーモードコーラス波と呼ばれる電磁波と共鳴して地球大気に降りこむことが挙げられる。この機構の放射線帯消失への寄与を定量的に評価するためには、この降りこみ電子の量を測定することが必要であるが、共鳴を起こしている磁気圏赤道面付近では降りこみ電子を同定することは難しい。一方、電子の降りこんでくる電離圏にはコーラス波は十分な強度で伝播してこない事が多く、電子と波動の対応がとりにくい。そこで、コーラス波による降りこみ電子が引き起こす脈動オーロラを、コーラス波の代用とすることが考えられる。このアイデアに基づき、日本の PARM チームでは 4 つの観測器-高エネルギー電子観測器 (HEP)、中間エネルギー電子観測器 (MED)、オーロラ撮像装置 (AIC)、磁力計 (AFG) を米国の観測ロケット RockSat-XN に搭載し、2019 年 1 月にノルウェーのアンドーヤにて打ち上げる予定である。このなかで、我々の開発した MED は 20-100keV の電子の降りこみをとらえる。これまでに、電子回路基板の性能評価試験、筐体の組上げ、改良などを実施し、測定するエネルギーより十分小さいノイズレベル ($< 3\text{keV}$) と太陽光の入射に耐えうる遮光性能を確認した。また、環境試験も問題なく完了し、観測器は現在、ロケットに搭載済みである。

PARM 計画: 観測ロケット RockSat-XN による高エネルギー電子マイクロバースト現象の観測

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PARM: Observations of microburst precipitation of high-energy electrons based on the RockSat-XN sounding rocket

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Microburst precipitation of high-energy electrons (higher than approx. 100keV) is frequently observed by low-altitude satellite. Recently, the microburst precipitation was successfully reproduced by numerical simulations based on pitch-angle scatterings of the electrons due to whistler mode chorus waves at off-equator region. Since the whistler mode chorus waves are likely related to the pulsating aurora activities, one can expect that relationship between the microburst precipitation and the pulsating aurora.

We have built PARM (Pulsating AuroRa and Microburst) instrument package to perform in-situ direct plasma measurements of the microburst phenomena during the pulsating aurora. PARM consists of high-energy electron instruments (HEP and MED, 20keV - 2MeV is covered), an auroral imager (AIC), and a magnetometer (AFG, a fluxgate magnetometer powered by the state-of-art ASIC device). PARM is already installed in the RockSat-XN sounding rocket operated by NASA Wallops, and will be launched in January, 2019 from Andoya, Norway.

In addition, we are participating in the LAMP (Loss through Auroral Microburst Pulsations) sounding rocket mission led by NASA GSFC and U. of New Hampshire, which will be launched in December, 2019. We will also provide an instrument package and coordinated ground-based observations to LAMP.

We will report on a status of PARM.

Effects of geomagnetic field and cold plasma on the generation of isolated proton aurora at sub-auroral latitudes

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Electromagnetic ion cyclotron (EMIC) waves in the magnetosphere cause pitch angle scattering of high-energy (several keV ~ tens of keV) ions via wave-particle interactions. Then, isolated proton aurora (IPA) is observed on the ground. EMIC waves propagate along the magnetic field line from the source region and are observed as Pc1 waves on the ground. In order to understand the effects of geomagnetic field and cold plasma on the wave-particle interactions, we investigated the curvature effects of background magnetic field and cold plasma density on the generation of EMIC waves.

In this study, we calculated the curvature of magnetic field line near the magnetic equator to estimate the curvature effects on the generation of the IPA. The IPA and related Pc1 waves were observed at Athabasca, Canada, using an all-sky EMCCD camera (110 Hz sampling) and an induction magnetometer (64 Hz sampling) at 05:30-06:00 UT on 17 February, 2017. The spectral characteristics of Pc1 waves changed from discrete elements to broadband waves when the IPA moved from higher latitudes to lower latitudes. Then, the gradient of magnetic field line near the magnetic equator, which is calculated by Tsyganenko 2002 model, became 15% smaller. The observation results support the importance of curvature characteristics for spectrum characteristics of EMIC waves.

Next, we compare the IPA observed at 01:30-02:00 UT on 2 January, 2016 at The Pas, Canada, with the differential total electron content (TEC) to investigate the relationship between cold plasma density and IPA. The TEC distribution can be equivalent to the cold plasma density in the plasmasphere. We observed two IPAs showing a clearly spatial gap between them. In the gap region of IPAs, we observed the increase of differential TEC value related to the spatial gap of IPAs. The gap region of IPAs was seen at 63.4 degrees in the invariant latitude and the observed local maximum in the distribution of differential TEC near the gap region of IPAs was seen in the vicinity of the gap at 64.7 degrees. Since the resonant energy of ions becomes small in the case of high plasma density, the IPA is not generated. Therefore, the existence of local maximum in the differential TEC indicates the importance of cold plasma density at the boundary of plasmopause for the generation of IPA.

These observations suggest that the curvature characteristics and cold plasma density are important in the generation of IPA. In this presentation, we will discuss the analysis results of the curvature characteristics and cold plasma density for the generation of IPA in detail.

Pc5 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 Pc5 auroral arc pulsations and field line resonances in the post midnight sector

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We report results from a detailed analysis of a Pc5 poleward moving auroral arc (PMAA) pulsation event using the ground-based THEMIS all-sky imager and magnetometer network observations and the coordinated onboard THEMIS-A, D, E satellites. It is found that (1) Pc5 PMAA pulsations occur in association with the enhancement of magnetic field and electric field oscillations observed near the equatorial plane of the magnetosphere, (2) the magnetic field, electric field, and velocity data observed by THEMIS-A, D, E show latitudinal/radial wave amplitude and phase shift structures, which is consistent with the field-line resonances (FLRs) theory, (3) ion and electron flux in the energy range of ~2-20 keV shows negative modulation in association with the FLRs oscillations, (4) Y component of velocity data show large (~40-50 km/s) velocity shear between THEMIS-D and E, where the orbit of THEMIS-D is almost the same as the orbit of THEMIS-E in X and Z position, but that is 0.2 Re separation in Y position, (5) enhancement of FLRs oscillations in the magnetosphere is ahead of auroral pulsations in the ionosphere and the period of FLRs oscillations is longer than that of auroral pulsations, (6) statistical results show that the occurrence maximum on magnetic local time is around 03 and that on solar wind speed is around 700 km/s. It is suggested the observed Pc5 PMAA pulsations are enhanced by FLRs oscillations produced by the Kelvin-Helmholtz instability-driven surface waves at the magnetopause. We will discuss the mechanism how to produce the field-aligned electric field that is directly relating to the generation of auroral pulsations.

Bounce Resonance between ~ 10 keV Protons and Poloidal Pc4 waves Observed by Van Allen Probe A

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We report the bounce resonance between ~ 10 keV protons and poloidal Pc4 waves with a wave frequency of 7.2 mHz observed by Van Allen Probe A on 28th January 2014. There were two onsets of the poloidal waves at 2010 and 2055 UT with simultaneous proton flux oscillations at 11.2-24.7 keV for the first event and at 8.3-17.4 keV for the second event. We determined that the poloidal waves are second harmonic waves. The onset coincidence of the waves and the flux oscillations implies a causal relationship between the second harmonic poloidal waves and the low energy protons. These proton flux oscillations are embedded in the injection of protons, suggesting the injection may create unstable particle distribution and excite the waves. Using the ion sounding technique (e.g., Min et al., 2017; Takahashi et al., 2018), we confirmed eastward propagation of the poloidal waves ($m > 0$) and m is estimated to be 170-270.

The m number of poloidal waves excited by the bounce resonance was not concerned in previous studies (e.g., Hughes & Kivelson, 1978; Liu et al., 2013), because they assumed a resonance condition of $w = w_b \sim 0$, where w is a wave frequency and w_b is a bounce frequency. We estimated the m number from a more general form of the resonance condition ($w - mw_d = Nw_b$, where w_d is drift frequency (Southwood et al., 1969), with the wave frequency of 7.2 mHz and the resonance energy of protons of ~ 10 keV), and obtained $m \sim +270$ for the bounce resonance ($N = +1$). Therefore, the bounce resonance with eastward propagating waves indeed took place in this event. It has been considered that westward propagating waves are generated through drift-bounce resonance (e.g., Takahashi et al., 1990; Dai et al., 2013; Oimatsu et al., 2018). This study, however, suggests that eastward propagating waves are also excited through the bounce resonance.

From the ion sounding technique, we also examined the radial gradient of the phase space density. The steep radially-outward gradient of the proton phase space density was found at the two onsets of the waves. This indicates that the injected protons enhance the phase space density in the outside region, and the resulting outward gradient provides energy for the waves.

Reimei and FAST observations on acceleration and transport processes of the electrons and ions in the midnight auroral regions

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Expecting new findings and essential understandings about the space-Earth coupling processes and mechanisms, several innovative space exploration missions are now being developed or under preparation for proposal and realization in all of the major space agencies in the world. Also in Japan, we are leading the FACTORS (Frontiers of formation, acceleration, coupling, and transport mechanisms observed by the outer space research system) mission by using multiple compact/micro satellites to be launched during 2025-2027.

The most important mission target of these space explorations is the magnetosphere-ionosphere-thermosphere coupling, which could also be applied to universal phenomena observed in the vicinities of magnetized/unmagnetized planets with atmospheres in our solar system and even exoplanets whose atmospheres are interacting directly with stellar winds. In the terrestrial case, firstly the midnight auroral regions are most crucial because they are characterized by the most essential and complicated plasma and upper atmospheric dynamics and electromagnetic phenomena initiated and affected through the whole magnetosphere-ionosphere-thermosphere coupling processes. In particular, the continuous energy and mass transports in these near-Earth space are mostly controlled by the electromagnetic field effects on the ionized atmospheric particles and the space plasmas.

While state-of-the-art measurements in these important regions of understanding the space-Earth(planet) couplings have not been achieved yet, the previous space missions, represented by DE-1/2, Viking, Freja, Akebono, POLAR, FAST, CLUSTER-II, and Reimei, have been providing us with considerable elemental knowledge. Particularly, the acceleration and transport processes regarding the electrons and ions could be surveyed in more systematic and carefully based on the database of these satellite missions. We, therefore, have been analyzing the observational results made mainly by Reimei and FAST because these data are open, accessible, and easily investigated with some updated tools. The high-time resolution data obtained by these two satellites are available for studying the spatial distributions or time variations of the space plasmas by field-aligned electric fields and the wave-particle interaction processes although there are not made any simultaneous observations by Reimei and FAST.

In this presentation, we discuss the similarities and differences seen in the Reimei and FAST observations by focusing on the dynamics of the electrons and ions at the altitudes ranging from 400-4000 km in the midnight polar regions.

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

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

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Plasma waves are an essential target for understanding electromagnetic environments in space. Thus, plasma wave observations by scientific satellites have been carried out. The plasma wave instrument is composed of electromagnetic sensors, pre-amplifiers, and plasma wave receivers. Plasma wave receivers are categorized into two types based on its data format: one is waveform receivers and other is spectrum receivers.

Plasma wave receivers require high-quality analog circuits to process weak signals, and it leads to an increase in the area of the receiver; however, demand for miniaturizing spaceborne instruments is increasing. We have been developed miniaturized plasma wave receivers using application-specific integrated circuits (ASICs). We realized greatly miniaturization by developing the ASIC for analog circuits which occupied the especially large area in the conventional receivers. However, the onboard digital processing is important in the recent plasma wave receivers, and the digital part of the receiver also occupies the large area. For further miniaturization, we develop a mixed-signal ASIC that includes all of the components of the plasma wave receiver.

Currently, we are developing an ASIC for the spectrum type receiver. The receiver is composed of three components: the analog part, the analog to digital converter (ADC), and the digital part. The observation frequency range of the receiver is from 10 Hz to 100 kHz. The main role of the analog part is amplifying and bandlimiting signals picked up by sensors. In addition, the analog part can be switched its observation frequency range because the receiver measures the observation frequency band by dividing it into three frequency bands: 10 Hz – 1 kHz, 1 kHz – 10 kHz, and 10 kHz – 100 kHz. The digital part includes the fast Fourier-transform (FFT) module and the controller. The FFT module calculates the frequency spectrum from the observed waveform. The controller controls all components in the receiver. To measure three observation bands in turn, the controller sends control signals to the analog part, the ADC, and the FFT module.

We successfully developed the analog part and the ADC by the ASICs. The size of the developed analog part is 4.3 mm x 1.2 mm, and the power consumption is 36 mW. The developed ADC has a 14-bits resolution and 33 MHz max sampling frequency, and its circuit size is 3.2 mm x 0.8 mm. We verified the function of the digital part by implementing on an FPGA. In addition, we developed and verified the receiver using the ASIC for the analog part and the ADC, and the FPGA for the digital part. In the presentation, we will present the detailed design and performance of the developed receiver and each component.

プラズマ波動は宇宙電磁環境の理解に不可欠な観測対象であり、そのため理学衛星にはプラズマ波動観測器が搭載されプラズマ波動の観測が行われてきた。プラズマ波動観測器は電磁界センサーとプリアンプ、受信器からなり、受信器は得られるデータの種類の、波形捕捉受信器とスペクトル受信器に分けられる。

プラズマ波動受信器は微弱な信号を処理するための高性能なアナログ回路やオンボードデジタル信号処理のためのデジタル回路が必要であり、大型になりやすい。その一方で、衛星搭載観測器は小型化が強く求められている。そのため、我々は特定用途向け集積回路 (ASIC) を利用し、プラズマ波動受信器の小型化を行ってきた。これまでに、従来の受信器で特に大きな面積を占めていたアナログ回路を ASIC で実装することにより、大幅な小型化を実現している。しかし、近年のプラズマ波動受信器においてはデジタル部も大きな面積を占めるようになってきている。そこで我々は受信器のさらなる小型化のため、受信器を構成するすべての回路を 1 つのアナログ・デジタル混載 ASIC チップに搭載することを目標とした、ワンチッププラズマ波動受信器を開発している。

現在開発している受信器はスペクトル型受信器であり、主にアナログ部・A/D コンバーター・デジタル部の 3 つの要素から構成される。受信器の観測帯域は 10 Hz - 100 kHz である。アナログ部はセンサーでピックアップされた信号を増幅・および帯域制限することが主な役割である。また、新型受信器は観測帯域を 10 Hz – 1 kHz, 1 kHz – 10 kHz, 10 kHz – 100 kHz の 3 つの帯域に分けて測定するため、外部からの制御信号によってアナログ部の観測帯域を切り替えられるよう設計されている。デジタル部には主にスペクトル計算を行うための FFT モジュールと受信器の制御を行うコントローラーが含まれている。コントローラーは 3 つの観測帯域を順に測定するために、アナログ部・A/D コンバーター・FFT モジュールのそれぞれに制御信号を送る。これにより、受信器は自律して観測帯域の切り替えを行いながら測定をすることができる。

これまでに、受信器のアナログ部および A/D コンバーターを ASIC で開発することに成功している。開発したアナログ部の面積は 4.3 mm x 1.2 mm、消費電力は 36 mW であった。A/D コンバーターは分解能 14 bit、最大サンプリング周波数 33 MHz であり、面積は 3.2 mm x 0.8 mm であった。また、ASIC として開発を行っているデジタル部について、

その動作確認のために FPGA を用いた検証を行った。さらに、ASIC で実現したアナログ部・A/D コンバーターと FPGA のデジタル部を組み合わせることで実際に受信器を構成し、その性能確認を行った。発表では、開発したスペクトル受信器の詳細な設計および、測定した各コンポーネントの性能について紹介する予定である。

アナログ・デジタル混載 ASIC による小型プラズマ波動受信器の開発

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Small Plasma Waveform Capture Receiver on the analog-digital mixed ASIC 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. However, the size of a plasma wave receiver on board satellites tends to be large to meet science requirements.

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.

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 waveform data of plasma waves sampled directly. The amount of original waveform data is large, so it is difficult to send them to a ground station without data compression. The onboard data compression is realized by a digital part of a plasma wave receiver. On the part of the digital processing, we succeeded in implementing the data compression logic on the FPGA in Kanazawa University. By using the logic in the FPGA, our research introduces the data compression logic onto an analog-digital hybrid chip. 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. In this presentation, the digital filters used in the waveform compression are implemented on the ASIC chip and its operation verification was carried out.

On the other hand, we modified the analogue part to reduce the noise level of the receiver developed in the previous research. The dominant noise of the developed ASIC analog part is that coming from the switched capacitor filter. Note that the switched capacitor filter is a type of active filter comprising amplifiers, capacitors, and switches. The role of the filter is to prevent from the aliasing effect by an A/D converter. We analyzed the noise source inside the switched capacitor filter by computer simulations and modified the circuits. The simulation results show the flicker noise of some broadband amplifiers is dominant in the low frequency range. Then, to reduce the flicker noise of the switched capacitor filter, we redesigned the gate area by enlarging the gate area to nine times as much as that in the previous design while keeping the ratio of the gate width and the gate length of some MOSFETs of the amplifier. As a result, we expect to reduce noise by 10 dB in the low frequency band. In the prototype of the redesigned chip, we confirmed the success in decreasing the noise level of the switched capacitor filter.

In this presentation, we present the details of the design of the circuits implemented on the chip and its performance of the chip.

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。したがって、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。しかし、要求性能上、プラズマ波動観測機器は大型になってしまいやすい。

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種類あり、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。

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アナログ回路と同一チップ上に実現する。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。本発表では波形圧縮回路のうち、デジタルフィルタおよびアナログ回路を同一チップ上で ASIC 化し、動作検証を行った。

また、本研究では、先行研究で開発された受信器アナログ部の低ノイズ化を行った。開発された波形捕捉型受信器の

ASICアナログ部では、その構成要素であるスイッチドキャパシタフィルタのノイズが支配的であることがわかっていました。スイッチトキャパシタフィルタのノイズレベルによって受信器のノイズフロアが決まっているため、その低ノイズ化が課題となっていた。スイッチドキャパシタフィルタについて、ノイズの解析を行った後、改良を施した回路を試作し、検証を行った。なお、スイッチドキャパシタフィルタは、アンプ、キャパシタ、スイッチで構成されているアクティブフィルタの一種であり、波形捕捉型受信器では、A/Dによるエリアシングの効果を防ぐ役割をもつ。

ノイズの解析はシミュレーションを用いて行った。この解析の結果、低周波帯域で支配的なノイズである一部の広帯域アンプのフリッカーノイズが支配的になっていることがわかった。そのため、アンプの一部のMOSFETのゲート幅とゲート長の比を保ったまま、ゲート面積を従来の9倍に拡大して再設計を行った。これにより、低周波帯域で10dBのノイズの低減を見込んでいる。

再設計したチップの試作では、フリッカーノイズ低減のため、一部のMOSFETのゲート面積を拡大した改良アンプを使用したスイッチドキャパシタフィルタと、比較用の改良前のアンプを使用したスイッチドキャパシタフィルタをチップ内に実現した。これを用いて、アンプ改良による低ノイズ化が実現しているかの検証を行い、設計通りの低ノイズ化に成功していることを確認した。

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および、今回試作したチップに搭載した回路の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。

Improvement of space environment tolerance in a plasma waveform receiver by using ASIC technology

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We have been investigating plasma waves (A few Hz to 10 kHz) to understand the magnetospheric dynamics. To capture plasma waves, we use a waveform receiver. It is required reduction of physical resources (mass, volume and power etc.), a wide operating temperature range (-60 to +100 Celsius degrees) and a high radiation tolerance (350 krad or more). We have been developing a waveform receiver by using ASIC (Application Specific Integrated Circuit) technology in order to reduce physical resources with a high tolerance for space environments. However, the conventional ASIC waveform receiver (hereinafter called ASIC receiver) was not accepted the requirements of environment tolerance. The main purpose is to achieve -60 to +100 Celsius degrees of operating temperature range and 350 krad or more of radiation tolerance for the ASIC receiver.

The conventional ASIC receiver did not operate at -60 Celsius degree in the circuit simulation result. The reference currents for the amplifiers in the conventional ASIC receiver are supplied by an external bias resistance (32k ohms) connected to the voltage source. The fluctuation rates of reference current are approximately plus or minus 6% in -60 to +100 Celsius degrees. It is not sufficient, because a threshold voltage of CMOS changes by ambient temperature. We added a temperature compensation circuit into the new ASIC receiver in order to supply the reference currents without the external bias resistance. By using the circuit simulation, we estimated the effects of the temperature compensation circuit on the operating temperature range (-60 to +100 Celsius degrees). From the simulation results, the fluctuation rates of reference current supplied by the temperature compensation circuit were approximately plus or minus 30% (-60 to +100 Celsius degrees), which is better for improving the operating temperature range. The new ASIC receiver can operate in the requirement of operating temperature range.

The radiation tolerance of conventional ASIC receiver cannot satisfy the requirement of 350 krad or more because the based amplifiers of the conventional ASIC receiver are weak for radiation. To improve the radiation tolerance, the surface area of amplifier in the new ASIC receiver was designed approximately 3.5 times larger than that for the conventional ASIC receiver. We did the radiation test for the conventional and new ASIC receivers by using the gamma ray of 400 krad to evaluate the radiation tolerances. From the radiation test results, the output noise (at 2.5 Hz) of conventional ASIC receiver degraded by approximately 6 dB from 310 krad. However, the output noise of new ASIC receiver was no change during the radiation test (until 400 krad). We consider the large surface area of amplifier can decrease occurrence rate of electron-hole pairs by radiation. The new ASIC receiver can operate in high radiation environments like a planetary mission.

In this presentation, we will present the improvement of space environment tolerance in a plasma waveform receiver by using ASIC technology in detail.

HF ドップラーサウンダーにより観測された ULF 帯電場の低緯度電離圏への伝送

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Transmission of ULF electric field to low latitude in magnetosphere-ionosphere current circuit as observed with HF Doppler sounder

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The geomagnetic sudden commencement (SC) and Pc5 pulsations often appear at high latitude and equator with the amplitude decreasing as the latitude decreases but increases at the dayside geomagnetic equator. The SC and Pc5 are caused by the magnetospheric currents and DP2-type ionospheric currents that flow from the polar ionosphere and are intensified by the Cowling effect at the equator (Araki, 1994; Motoba et al., 2002). The electric fields of the SC and Pc5 have been observed with the HF Doppler sounders at low latitude, which are well correlated with the equatorial electrojet (EEJ) (Kikuchi et al., 2016; Motoba et al., 2004). These observations suggest that the electric fields are potential fields associated with the ionospheric currents. To confirm that the Pc5 electric field is transmitted through the magnetosphere-ionosphere current circuit, we made correlation analyses between the Pc5 electric fields at low latitude and geomagnetic Pc5 at high latitude and equator on both the day- and night-sides. We show that the Pc5 electric fields are well correlated with the global DP2-type ionospheric currents in the same manner as the SC electric fields. To identify the location of the field-aligned currents (FACs) feeding the ionospheric currents, we show that a stormtime Pc5 changed its polarity at 64 degs in the morning and 58 degs in the afternoon sectors. The reversal of the polarity may indicate the location of the FACs. We further show that the low latitude PC5 is larger in amplitude on the nightside than on the dayside, suggesting that the PC5 around the midnight is strongly affected by the direct effects of the FACs. We further show that electric fields of the ULF pulsations with periods covering the Pi2 (1-3 min) are well correlated with the EEJ. Consequently, the ULF range electric fields at low latitude are associated with the DP2-type ionospheric currents flowing from the high latitude to the equator. The ULF electric fields are transmitted from the magnetosphere to the equatorial ionosphere through the magnetosphere-ionosphere current circuit, carried by the transverse (Alfven) waves and TM0 mode waves in the magnetosphere and Earth-ionosphere waveguide, respectively.

磁気急始 (SC) や Pc5 地磁気脈動は磁気圏電流の効果に電離圏電流効果が重畳するために、高緯度と赤道で同時に現れる。SC, Pc5 の電場は低緯度で HF ドップラーサウンダーにより観測され、電場と赤道ジェット電流の間に強い相関のあることが知られる (Kikuchi et al., 2016; Motoba et al., 2004)。本論文では、低緯度 HF ドップラーサウンダー、極赤道磁力計網のデータを解析し、低緯度電離圏の Pc5 電場が磁気圏電離圏電流回路を經由して電離圏に流れる導電性電流に伴うポテンシャル場であることを示す。この結果は、Pi2(1min) や DP2(30min) など広い周期範囲の地磁気変動にも適用されることを示す。

Highly structured FACs near the poleward boundary of the duskside auroral oval during geomagnetically quiet conditions

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The concentric rings of the Region 1 and Region 2 field-aligned current systems are well-defined large-scale features in the high-latitude ionosphere. The duskside part of the Region 1 sometimes has very strong current intensities, while the Region 1 can be extremely diminished mostly for northward IMF. In this study, using multispacecraft SWARM data and ground-based aurora imager data, we clarify the features of the highly structured field-aligned currents embedded in the diminished duskside Region 1. The magnetic field measurements from SWARM A and SWARM C after May 2014 are ideal for understanding the highly structured field-aligned currents because they are ~5 to ~10 s apart along track. By examining magnetic field data obtained by these satellites in the duskside sector during geomagnetically quiet conditions, we took many events in which relatively large amplitude small-scale (less than 100 km along track) variations are embedded in the diminished Region 1. We found that in almost all cases the relatively large amplitude small-scale variations are fairly well correlated between the SWARM A and lagged (~5 to ~10 s) SWARM C data. This indicates that the observed magnetic field variations represent the spatial structure of the multiple field-aligned currents, not the Alfvén wave. There is no doubt that several pairs of upward/downward field-aligned currents occur in the diminished Region 1. Examination of the all-sky imager data obtained at Longyearbyen, Svalbard during the passage of SWARM A and SWARM C through the field-of-view of the all-sky imager reveals that those multiple pairs of the field-aligned currents were in the region of the modest auroral intensification near the poleward boundary of the auroral oval. DMSP particle observations are also consistent with the existence of the multiple field-aligned current pairs. We will show the occurrence characteristics of the highly structured field-aligned currents in the duskside Region 1, and discuss the possibility of the generation of the multiple pairs of the field-aligned currents in the low-latitude boundary layer.

X線天文衛星「すざく」による太陽活動極大付近における木星観測

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Suzaku observations of Jupiter X-rays around solar maximum

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We report on results of *Suzaku* observations of Jupiter X-rays in 2012 and 2014 and discuss future observational prospects. Recent X-ray observatories have discovered X-ray emission from objects in our solar system (Bhardwaj *et al.* 2007). Jupiter is the largest and magnetic strongest planet in the solar system.

Suzaku found the diffuse X-ray emission in 1-5 keV associated with Jupiter's radiation belts around solar minimum in 2006 thanks to its low background X-ray CCDs (Ezoe *et al.* 2010). However, its emission mechanism was unclear. We thus conducted additional *Suzaku* observations in 2012 and 2014 around solar maximum and successfully found the diffuse X-ray emission. From its power-law spectrum and no significant change of X-ray flux in 1-5 keV, we concluded that it is most probably caused by inverse-Compton scattering of solar photons by tens MeV electrons in the Jupiter's magnetosphere.

本講演では X 線天文衛星「すざく」による 2012、2014 年の木星観測の結果について報告する。近年の X 線観測衛星の活躍により、太陽系天体からの X 線放射が多数発見されている (Bhardwaj *et al.* 2007)。これら太陽系天体からの X 線の放射メカニズムについては、徐々に明らかになってきているものの未解明な部分が多い。木星は太陽系最大の惑星であり、数百木星半径にも及ぶ巨大な磁気圏とその内部 6 木星半径には衛星イオからの火山ガスを源とするイオプラズマトラスを持つ。木星 X 線の放射領域、メカニズムについては、*Chandra* や *XMM-Newton* などによる先行研究で太陽活動との関係が議論されている。

「すざく」による 2006 年の木星観測で、世界で初めて木星の周りに広がった硬 X 線放射 (1-5 keV) が確認されている (Ezoe *et al.* 2010)。「すざく」は高感度かつ低バックグラウンド検出が特徴であり、この広がった硬 X 線放射に有利である。この放射の起源として、磁気圏粒子による太陽光子の逆コンプトン放射などが議論されているが、詳細は未解明なままである。我々はこの観測に対する追観測として、太陽活動が活発な 2012、2014 年に「すざく」による木星観測を行った。

両観測において、2006 年観測同様に、硬 X 線帯のイメージで木星の周りに広がった X 線を確認し、同帯域のスペクトルがフラットなべき関数で再現できることを確認した。木星本体からの放射と広がった放射を切り分けたところ、広がった放射の X 線光度は 2006 年に対して 1-2 倍程度であった。これは逆コンプトン放射と同じく高エネルギー磁気圏粒子を起源に持つ木星シンクロトロン電波放射の変動 (Santos-Costa *et al.* 2008) と同程度であり、先の議論を後押しする結果と言える。本講演ではこれら解析の詳細な結果と今後の木星 X 線観測の展望を述べる。

流出イオンによる太陽風 Mass-loading の際の太陽風運動エネルギーの M-I 結合系への取り込みは無視できない

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Importance of mass-loading energy extraction from the solar wind to the ionosphere through positive feedback M-I coupling

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<http://www.irf.se/%7Eyamau/index.html>

Cluster statistics in the high-latitude magnetospheric boundary (exterior cusp, magnetosheath, plasma mantle) showed that ion loss rate from the open part of the polar magnetosphere increases exponential to Kp up to Kp=7, with number density ratio of O/H about 1% in average. This means that the mass density of escaping O⁺ compared to the solar wind is about 20%, which can no longer be ignored. In fact, Cluster observed substantial deceleration of the solar wind H⁺ while acceleration of O⁺ in plasma mantle. The conservation of anti-sunward momentum means, for inelastic mixing of O⁺ into the H⁺ flow, that the kinetic energy is no longer conserved, with about 10% loss when the O⁺ velocity reach the H⁺ velocity. The energy conversion rate, simply calculated from the momentum conservation, is proportional to total mass flux of O⁺ (F_O) into the incident solar wind and to the square of the solar wind velocity (u_{sw}²), and not dependent on the injection area or solar wind density.

Unlike Mars or comets where the energy is converted to cycloid motion (random gyration), magnetic connectivity to the ionosphere (load) for the Earth's case allows the energy is converted to the electric current in the Magnetosphere-Ionosphere coupling system. Applying the observed O⁺ value and area, this means 10¹⁰⁻¹¹ W, and is large enough to explain the electric current system flowing in the cusp region, which is the most intense current system in the dayside.

Since the ion heating due to the Joule heating of such an ionospheric current system is the main driver of the ion outflow, the entire cycle constitute a positive feedback energy extraction, explaining the observed exponential dependence of the escaping flux to Kp or solar wind velocity. Inversely, it is difficult to explain the exponential dependence to Kp without such a positive feedback, because the solar wind dependence gives only near-linear dependence to the solar wind "coupling function", which is at most u_{sw}⁴ but not exponential. Considering the ancient condition that corresponds to Kp=9-10, the mass-loading is extremely important in the atmospheric evolution.

Thus the ionosphere and escaping ions in the M-I coupling system is more important than we traditionally thought. The present positive feedback model with the mass-loading effect assumes that information of "deceleration" propagate upstream faster than the information of transversal electric field caused by O⁺ deflection (shift of the guiding center), such that electric field by the H⁺ deceleration appears before O⁺ pickup motion.

Cluster 衛星の高緯度磁気圏境界領域 (cusp, plasma mantle, magnetosheath) のイオンデータ (>30 eV) の統計によると、地球から直接太陽風へ (磁気圏尾部に入らずに) 流出するイオンの量は、中高度 (DE-1 など) の結果同様に地磁気活動 Kp に対して指数関数的に増加していることが判明している。これらの領域では O/H 比 (電離層起源酸素イオンと太陽風の比) が 1%程度あることも分かっている。Mass-loading という視点では、密度比が 1%でも、質量密度比に直すと 2 割近くとなり、太陽風の運動エネルギーが 1 割近くが熱エネルギーか電磁エネルギーに変換され得ることを意味する。最大値は地球起源 O⁺と太陽風 H⁺の速度が同じになった時点で達成される (それは非弾性衝突と同じ効果をもたらす)。この数字は運動量保存則を用いているので、酸素と太陽風の混合プロセスに依存しない。

これが火星や彗星であれば、この余剰エネルギーの大半は、サイクロイド運動という巨視的にはランダムな運動 (熱エネルギー) に変換されようが、地球の場合は、サイクロイド運動の初期の電場加速で起こるイオンと電子の分離が、分極電場として素早く電離層に伝わることで、電磁エネルギーに変換され得る。要するにダイナモであり、そのエネルギー総量を概算すると 10¹⁰⁻¹¹ W となって、実にカスプ電流系のエネルギーに合致する。このエネルギーが電離層でジュール熱等へと変換される際にイオン流出のエネルギーにも使われることまで考慮すると、このダイナモは全体として positive feedback を形成する。となれば、このダイナモを具体的な形状で定式化することは、極域の M-I 結合系を考える上で不可欠である。

太陽風から見た場合、磁場に対して通して電離層につながっている (open) かどうかでダイナモの有無が議論されてきたのに対し、ここでは太陽風に流出イオンが混ざるかどうかでダイナモの有無が決まる。その意味では磁場でなくイオンで電離層との結合 (open か closed か) が決まる。そこで流出イオンが太陽風 (カスプを含む) にぶつかる最上流を

モデルの境界とし、そこでの太陽風速度 (u_{sw}) と有効断面積 (S)、及び、太陽風内に入り込む流出イオンの質量 flux 総量 (F_O) として簡単なモデルを組んだ。それによると、失われる太陽風運動エネルギーの総量 (その半分だけが流出イオンの夜側への加速に使われる) は、 $F_O \propto u_{sw}^2$ のみに比例し、 S は式の中に入ってこない。また運動エネルギーのみを議論しているので太陽風磁場も式の中に入ってこない。それは極域昼側の S_q 振幅が太陽風速度に最も依存している観測に合致する。

この式において、 F_O は K_p に対して指数関数的に依存しており、 u_{sw}^2 の項よりも変動が極めて大きい。それは、イオン流出が K_p に対して指数関数的に増えるという経験則が K_p が 8 以上のいわゆる宇宙天気イベントでも成り立つことを示唆する。ここで、リコネクションや KH 不安定など、地球磁場を通して変換されるエネルギーが太陽風速度等のべき程度にしか比例していないことを考えると、地磁気活動が極端に高くなるほど、流出イオンの Mass-load によるダイナモの重要性が増し、場合によっては地球磁場を通したダイナモよりも昼側の電離層活動に影響を与えうることが予想される。

極めて高い地磁気活動は、数十億年の過去では今よりはるかに頻繁に起こっていたと考えられている。従って、過去においては電離層並びに流出イオンの役割、並びに流出量は今以上にあった筈だ。それを概算すると 40 億年で現在の地球大気と同等の量が既に流出しきった勘定になる。そのうちの酸素は海洋から供給されるが、窒素がそういう訳にはいかない。そして O/N 比が数パーセント変化するだけでバクテリア等の活動が大きく変わることを考慮すれば、イオン流出は地球生命圏の進化にも影響を与えた可能性がある。かように電離層の役割は今まで考えられていたよりはるかに重要である。

SuperDARN 北海道-陸別第二レーダーのステレオモードによる SAPS 擾乱構造の高時間空間分解能観測

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High temporal / spatial resolution observation of SAPS perturbations using the SuperDARN Hokkaido West radar stereo mode

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We show the results of the high temporal resolution / two-dimensional observation of small-scale SAPS wavy perturbations during the September 8, 2017 geomagnetic storm, using the stereo mode operation of the SuperDARN Hokkaido West (hkw) radar. The Hokkaido West radar, deployed in October 2014, is the second SuperDARN radar located in Hokkaido, Japan and one component of the SuperDARN HOKkaido Pair of (HOP) radars. The Hokkaido West radar deploys stereo mode scan system, where the radar can emit two radar beams with two different radar frequencies and beam directions simultaneously. Using this stereo mode, it can monitor the ionosphere and upper atmosphere both with 1 min 2-dimensional scan and 3 sec camping beam, enabling both two-dimensional (1 min) and high temporal resolution (3 sec) data acquisition. We succeeded in observing the SAPS perturbation signatures having various temporal scale of from 1 min to several tens of minutes. One of them is disturbance from 1228 to 1234 UT, with about 1 min periodicity and 10 degrees longitudinal wavelength, propagating westward. The temporal scale of SAPS perturbation is obviously shorter than previously reported values (about 5 mins). Possible generation mechanisms of these perturbations will be discussed. Coordinated study with the Arase spacecraft is also in progress.

Study of Ionospheric Conductivity Dependence of the Subauroral Polarization Streams 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 ionospheric conductivity dependence, especially 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, and we limited the time range of the analysis to 3-8 UT (12-17 LT). In addition, in order to achieve a more precise mapping of scattering locations, we applied a new empirical virtual height model introduced by [Chisham et al., 2008] to the SuperDARN Hokkaido East radar. The new model uses different coefficients in the model when mapping backscatter targets propagate via different propagation paths. 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. We also took into account the effect of EUV absorption in the atmosphere. As a result of the statistical study, we find that SAPS tend to appear when the SZA is larger than 95 degrees, and that the minimal threshold of illuminated ionospheric altitude for SAPS occurrence is about 126 km, which is just above the altitude of the peak of Pedersen conductivity. This result suggests that the low background Pedersen conductivity plays an important role in the generation of SAPS by leading to a positive feedback which enlarge the electric field that consequently generates SAPS. In addition, in order to investigate the magnetospheric electric field during SAPS events, we are collecting the conjunction observations of SAPS by the Arase satellite and SuperDARN Hokkaido East radar. By using the electric field data and particle flux data provided by Arase, we expect to examine the variation of the electric field when SAPS occurs, which would help us further understand the mechanism of SAPS.

SuperDARN データへの位相差法・振幅比法の適用による FLR の高精度同定

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High-resolution identification of the FLR in the SuperDARN data by using the gradient method

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The FLR (Field Line Resonance) takes place where the frequency of an incoming wave matches the eigenfrequency of magnetospheric magnetic field lines. The FLR can be identified from the unique manner of change in the amplitude and the phase of the FLR-related waves across the resonant point. From the ground-identified FLR frequency one can estimate the magnetospheric plasma density.

Since the field-line eigenfrequency oscillates the ionospheric plasma, too, one can identify the FLR from the ionospheric plasma velocity. We have used the line-of-sight plasma velocity (VLOS) data obtained by SuperDARN radars to identify the FLR and estimate the magnetospheric plasma density. Unlike the ground magnetometer data, the SuperDARN data is two-dimensional, enabling two-dimensional estimates of the magnetospheric equatorial plasma density and magnetospheric region identification.

To achieve that, it is important to identify as many as possible FLR events. Overlapping of non-FLR waves/perturbations "hides" FLR events. As a countermeasure to this problem, the so-called gradient method has been applied to the ground magnetometer data; this method cancels out the overlapping signals by dividing the data from a magnetometer by the data from another magnetometer having an adequate distance from the other along the same meridian. This method is effective since the FLR frequency tends to depend on the latitude more strongly than the overlapping signals.

The gradient method is also applicable to the VLOS data from the SuperDARN radar. We have been doing that, and the initial analyses have led to the identification of FLR from VLOS's at adequately separated two Range Gates. More details will be presented at the meeting.

FLR (Field Line Resonance) とは、太陽風領域から磁気圏内に侵入・伝搬してくる波動の周波数が、磁気圏内の地球起源の磁力線の固有振動周波数と同じ値になる位置で、共鳴現象が生じて磁力線固有振動が励起される現象である。その振幅と位相は共鳴周波数の近傍で特徴的な変動パターンを示すので、FLR event と同定できる。そして、その周波数を用いて、観測している磁力線沿いの磁気圏プラズマ密度分布を地上から推定できる。

磁力線固有振動は電離圏プラズマも振動させるので、電離圏プラズマの速度のデータからも FLR を同定でき、我々は SuperDARN radars によって観測された電離圏プラズマ速度 (VLOS: Line-of-sight velocity) のデータに FFT を適用した結果を図示・目視して FLR を同定しその周波数から磁気圏プラズマ密度を推定している。SuperDARN は地上磁力計と異なり電離圏の 2 次元領域を連続的に測定できるので、磁気圏赤道面のプラズマ密度分布も 2 次元的に推定でき、プラズマ圏など磁気圏内領域の同定が出来ると期待される。

ただ、その為には、FLR を高精度で同定しそれによりイベント数を増やす事が重要である。地上磁場中にも電離圏プラズマ速度中にも FLR 以外の波動・擾乱が重畳している事が多く、それにより FLR の同定が難しくなる。

この問題の解決の為に、地上磁場解析においては位相差法・振幅比法と呼ばれる方法が用いられている。これは、FLR 周波数は緯度依存性が強いのに比較して、重畳している波動・振動はグローバルで緯度依存性が FLR より弱い事が多いので、緯度方向に適度に離れた 2 つの磁力計のデータの比をとる事で重畳波動を cancel out して FLR 現象のみ取り出す事ができる、というものである。

この方法論は SuperDARN の VLOS データにも適用可能と考えられ、我々はその適用研究を開始した。地上磁力計位置に対応するものとして、各ビームの Range Gates (RGs) を使用する。2 つの RGs の VLOS データに位相差法・振幅比法を適用する。初期結果として、この方法により FLR が実際同定出来た例を見出している。またその同定の精度は 2 つの RGs 間の距離にも依存する事を見出している。その詳細、またその後の進展については会場での発表時に説明する。

Revisiting the dynamic process of field-aligned current generation

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As shown by Vasyliunas [1970], the magnetospheric diamagnetic current has a finite divergence when it crosses the region with a finite B gradient and connects to the Field-Aligned Current (FAC). A pressure gradient force, the origin of the diamagnetic current in a force balance to the Ampere force, never twists plasma flow. While for the development of magnetic shear, which corresponds to FAC, combination of Ampere's law, Faraday's induction law and MHD Ohm's law require the gradient of plasma vorticity along B -field. In other words, for the existence of a quasi-steady FAC in the MHD scheme, the plasma vorticity along the B -field is inevitably required.

Of course, for the development of plasma vorticity, we need a dynamical process that twists the plasma. What is the dynamical process that twists the plasma as FACs are generated due to the divergence of the diamagnetic current? A conventional answer to this question is a mode conversion between the compressional mode and the Alfvén mode when the diamagnetic current is growing (in inductive process). However, in principle, the magnetosphere-ionosphere coupling system forms a dissipative structure in the open solar-terrestrial system. Therefore, even in a macroscopic quasi-steady system, the constant conversion from the thermal energy to the magnetic energy and the internal mode conversion from magnetic compression to the magnetic shear should continuously take place. In this sense, we need to revisit the dynamical process of FAC. In this presentation, we will discuss what is the dynamical process and what is the quasi-steady state of FACs in a dissipative structure of the open magnetosphere-ionosphere system.

Multiple electron precipitation spots in the cusp and subsequent equatorward expansion of aurora beyond the cusp

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Aurora image data obtained from ground based all-sky imagers have shown that multiple brightening spots often appear in the cusp. This indicates that the electron precipitation having a relatively large energy flux can occur in a patchy manner. In this study we understand how the appearance of those electron precipitation spots in the cusp is related to a midday lower-latitude auroral expansion feature, which is sometimes seen in the near-noon meridian equatorward of the cusp. This feature represents the electron precipitation having a large energy flux expands equatorward beyond the cusp. On the basis of observations of dayside auroras from an all-sky imager at Longyearbyen, Svalbard, and in situ observations of precipitating particles and magnetic field from DMSP spacecraft that flew over the aurora, we identified an event in which the intense cusp electron precipitations became localized in a narrow range of MLT near noon, and eventually the aurora started to expand equatorward of the cusp. This observation suggests a close relationship between the occurrence of the electron precipitation spots in a narrow range of MLT and the subsequent equatorward expansion of the electron precipitation region beyond the cusp. We will show detailed results about the motion of the auroral spots by analyzing the aurora images obtained at two wavelengths, 557.7nm and 630.0 nm, and discuss the cause of the equatorward expansion of the electron precipitation region beyond the cusp.

Statistical Study of Selective Transport of Energetic Oxygen Ions During Magnetic Storms Observed by Van Allen Probes in 2013-2017

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The ion transport from the plasma sheet to the ring current is the main cause of the development of the ring current. The energetic (>150 keV) ring current ions are known to be transported diffusively in several days [e.g., Gkioulidou et al., 2016]. Mitani et al. 2018 suggested that energetic oxygen ions are transported closer to the Earth than protons due to the diffusive transport caused by a combination of the drift and the drift-bounce resonances with Pc3-5 ULF waves during the April 24, 2013 magnetic storm. We hereafter call the energetic oxygen transport as the selective transport. In order to understand its occurrence conditions and roles in the ring current development, we investigate the phase space densities (PSDs) between protons and oxygen ions with the first adiabatic invariants (μ) of 0.1 keV/nT-2.0 keV/nT observed by Van Allen Probes at $L \sim 3-6$ during 90 magnetic storms in 2013-2017. We identified the selective transport as an event in which that oxygen PSDs increases while proton PSDs do not increase in >0.5 RE band of L-shells in >0.5 keV/nT range of μ . Among the 90 storms, 33% were accompanied by the selective transport events. The selective transport tends to occur in the night-dusk sector and in the lower-L shells during larger storms. When the selective transport occurs, the enhancements of Pc4 and Pc5 oscillations obtained by wavelet analysis of ground magnetic field data (e.g. from the CARISMA and THEMIS GMAG) are detected in global MLT at $L > 4$ and at $L > 3$, respectively. It suggests combination of the drift-bounce resonance with Pc4 oscillations and the drift resonance with Pc5 oscillations can be the cause of the selective transport of energetic oxygen ions. Contribution of the selective transport to the magnetic storm intensities is roughly estimated to be ~ 20 % at most.

Reference:

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2成分速度分布関数フィッティングで得られた磁気圏プラズマの低温および高温成分の特性

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Characteristics of hot/cold components of magnetospheric plasma derived from two-component fits of velocity distribution functions

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Heating and acceleration of magnetospheric plasma have been studied using in-situ plasma and field observations. A large number of observations reported two distinct plasma populations with different temperatures in the Earth's magnetosphere [e.g., Seki et al 2003]. However, the dominant heating/acceleration mechanisms and regions are not well understood. Moreover, it remains unclear whether the heating/acceleration mechanisms depend on mass. Only a few satellite missions have been able to observe the thermal component of magnetospheric plasma with mass determination. Therefore, a small number of studies focused on mass-dependent processes in the typical energy range ($<1-10$ keV) of magnetospheric ions. In this study, we first separate the plasma into hot and cold populations, and then perform statistical analysis for each population.

The Fast Plasma Investigation (FPI) instrument on board the MMS satellite, which is in a low-inclination elliptical orbit with an apogee of about 24 Re and a perigee of about 1000 km, measures the three-dimensional distribution function in velocity space every 4.5 seconds in an energy range of a few eV to 40 keV [Pollock et al. 2016]. Using data for a period of September 2015 to September 2017, we examined density and temperature spatial distributions for hot and cold plasma populations. Specifically, we performed two-Maxwellian fitting to the observed three-dimensional distribution functions. Two different populations were clearly identified inside the magnetosphere, but not in the magnetosheath. Next, we divided an equatorial plane into $0.5 \text{ Re} \times 0.5 \text{ Re}$ bins and then calculated the median of density and temperature for each bin for each population. The hot plasma has a higher temperature on the dusk side than on the dawn side. Also, in the presence of two component plasmas, the temperature of the hot plasmas is several tens of times higher than that of the cold plasma. We will perform similar analysis with the data obtained by the HPCA instrument on board MMS to investigate mass dependence of the heating/acceleration mechanism. We will also discuss the acceleration and mixing processes of cold plasma by focusing on oxygen ions of ionospheric origin.

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。磁気圏において、熱いプラズマと冷たいプラズマが同時に存在していることが報告されているが、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・加速機構がイオンの質量によって異なっているのか未解明である。磁気圏プラズマを熱い成分、冷たい成分に分離することは磁気圏におけるイオンの加速、加熱メカニズムの理解に重要な手がかりを与える。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、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、まずイオン種を区別しない観測を用いて、プラズマを熱い成分と冷たい成分に分離し、それぞれに対して統計解析を行う。

近地点 1000km から遠地点 24Re の範囲を周回する MMS 衛星に搭載された FPI 観測器は数 eV~40keV の電子、イオンを約 4.5 秒の時間分解能で観測している。本研究では FPI 観測器により得られたデータを用いて磁気圏に存在する熱いイオン、冷たいイオンそれぞれの密度、温度の空間分布の平均的な描像に関して統計解析を行った。具体的には、2015 年 9 月 1 日から 2017 年 9 月 1 日までに得られた 3 次元速度空間の分布関数を 2 成分 Maxwell 分布を仮定してフィッティングを行い、熱いプラズマと冷たいプラズマに分離した。2 成分のプラズマは磁気圏内部で多く見られ、シース領域ではあまり見られなかった。そして磁気赤道面付近の 6Re-24Re の領域を $0.5\text{Re} \times 0.5\text{Re}$ のビンに区切り、各ビンの密度、温度の中央値を示した空間分布図をそれぞれの成分毎に作成した。熱いプラズマはプラズマシートの夕方側が朝側と比べて高温になっていることがわかった。また二成分プラズマが存在する場合、熱いプラズマの温度は冷たいプラズマの数 10 倍になっていることがわかった。今後は HPCA 観測器により得られた酸素イオンのデータも用いて、冷たいプラズマの起源、加速過程、混合過程を議論する予定である。

二重殻トップハット式静電型エネルギー分析器の構想と数値設計

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A concept and numerical design of double-layered top-hat type electrostatic energy analyzer

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It is well known that the terrestrial and planetary magnetospheres and the interplanetary space are filled with charged particles such as electrons and ions, which are so-called the space plasma, and in-situ observations of the space plasmas have been conducted by using numerous satellites carrying particle instruments, such as the top-hat type electrostatic energy analyzers. Essentially, obtaining three-dimensional velocity distributions of the space plasmas or energy-pitch angle distributions helps us understand the dynamics of the space plasmas. In the top-hat type electrostatic energy analyzer, a potential difference is applied between two dome-shaped electrodes separated by a gap so that the charged particles with an appropriate energy pass through the gap between these electrodes to be detected as signals. Furthermore, the top-hat type analyzer is cylindrically symmetric and has a 360° planar field of view, which means the top-hat type analyzer can independently measure the distributions of the angle and energy of incident particles and also that three-dimensional velocity or energy-pitch angle distributions can be obtained by the satellite spin motion. Because of this advantage, the top-hat type electrostatic energy analyzers have conventionally been installed in the satellites such as INDEX and ERG of Japan in order to measure the space plasmas.

The top-hat type electrostatic energy analyzers can measure the ions when a negative potential is applied to the inner electrode and the electrons by a positive potential with the outer electrode grounded. In the prevailing design of the top-hat type analyzer, the sensor heads separate for the ion and electron observations, respectively. In accordance with the recent miniaturization of the satellites, the weight and space of the instruments mounted on the small and micro satellites are getting severely restricted. If two sensors are combined into one sensor head, it is possible to save both weight and space on the small and micro satellites. Therefore, we are now developing double-layered top-hat type electrostatic energy analyzer which can simultaneously measure the ions and the electrons with the same sensor head.

Our concept is to combine two sensors into one sensor head for electron and ion observations, and we design the shapes of the collimator and the double-layered dome-shaped electrodes for applying a negative potential to the central electrode with the inner and outer electrodes grounded. In this design, the electrons and the ions with appropriate energies pass through the inner gap and the outer gap, respectively. We have been making the numerical simulations using SIMION as a charged particle simulator program in order to investigate the performance and characteristics as the electrostatic analyzer and confirmed that the electrons and the ions can be analyzed with the same sensor head. So far, we are considering the detection unit using Time-Of-Flight velocity spectrometer for the discrimination of the ion species as the part where the ions are detected after the electrostatic energy analysis, and an assembly of micro channel plates is being expected for the electron detection.

地球と惑星の磁気圏及び惑星間空間は電子とイオンのような荷電粒子、いわゆる宇宙プラズマで満たされていることはよく知られており、宇宙プラズマのその場観測はトップハット式静電型エネルギー分析器のような粒子計測器を搭載しているたくさんの人工衛星を使うことによって行われている。基本的には、宇宙プラズマの3次元速度分布またはエネルギー・ピッチ角分布を得ることは私たちが宇宙プラズマのダイナミクスを理解するのに役立つ。トップハット式静電型エネルギー分析器では、隙間によって分けられた2つのドーム形の電極間に電位差がかけられ、適切なエネルギーを持った荷電粒子がこれらの電極間の隙間を通過して信号として検出される。さらに、トップハット式分析器は軸対称で、 360° の平面視野を持ち、このことはトップハット式分析器が入射する粒子の角度とエネルギーの分布を独立して測定できることとその上3次元速度またはエネルギー・ピッチ角分布が人工衛星の自転運動によって手に入れることが出来ることを意味している。この利点のため、トップハット式静電型エネルギー分析器は宇宙プラズマを測定するために日本のINDEXやERGのような人工衛星に慣習的に搭載されている。

トップハット式静電型エネルギー分析器は外側の電極をGNDにした状態で負の電位が内側の電極にかけられているときにはイオンを測定することができ、正の電位ときには電子を測定できる。トップハット式分析器の普及している設計では、センサーヘッドはイオンと電子の観測のために、それぞれ分かれている。最近の人工衛星の小型化に応じて、小さくて微小な人工衛星に搭載される機器の重さと場所は大幅に制限される。2つのセンサーが1つのセンサーヘッドにまとめられれば、小さくて微小な人工衛星で重さと場所の両方を確保することが可能である。従って、我々は今回同じセンサーヘッドでイオンと電子を同時に測定できる二重殻トップハット式静電型エネルギー分析器を開発している。

我々の構想は電子とイオンの観測のために2つのセンサーを1つのセンサーヘッドにまとめることであり、我々は内側と外側の電極をGNDにした状態で中央の電極に負の電位をかけるためにコリメーターの形状と二重殻のドーム型の電極を設計する。この設計では、適切なエネルギーを持つ電子とイオンが内側の隙間と外側の隙間のそれぞれを通過する。

我々は荷電粒子シミュレータープログラムとして SIMION を使って静電分析器としての性能と特徴を調べるために数値シミュレーションを行ったり、電子とイオンが同じセンサーヘッドで分析されることを確かめたりしている。今のところ、我々は静電エネルギー分析の後にイオンを検出する部分としてイオン種を区別するために TOF を使った検出部を考えており、電子の検出には MCP を使用することを予定している。

衛星搭載機器開発に向けた校正設備のための粒子ビームモニタリングシステムの開発

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Monitoring systems for characterizing charged-particle beams in the calibration facilities for space-borne instruments

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For the space explorations, particularly the in-situ observations of the planetary space and upper atmospheres of the Earth and planets, technologies related to particle instruments are very important in order to carry out quantitative in-situ measurements of space plasmas and atmospheric neutral particles. As one of the experimental facilities necessary for the developments of these particle instruments, advanced beamline calibration facilities are crucial for performing the calibrations of the particle instruments by emitting electron or ion beams simulating the space and upper atmospheric particles in vacuum chambers. The characteristics of the beamline facilities largely affect the calibration results of the particle instruments so that the homogeneities of the two-dimensional (2D) distributions of cross sections and the energy and angular dispersions of the beam fluxes are very important in the developments of the particle instruments. However, these characteristics of the beamlines have not been investigated in quantitatively and routinely so far.

Since we are constructing the beamline calibration facilities in our institute of Nagoya University, we should also develop a beamline monitoring system as an important component of our facilities in order to systematically obtain various types of data regarding the beamline characteristics. Our beamline monitoring system consists of two subsystems: one is for monitoring the 2D cross sections of the beam fluxes and another for measuring the energy and angular dispersions according to horizontal displacement. The subsystem monitoring the 2D cross sections of the beam fluxes is almost completed by combining horizontal and vertical linear motion stages and a multi-anode Micro Channel Plate assembly (MCP), and we have already developed a C#-language program package that controls the instruments, obtains count data from the MCP, compensates time variations of the beam fluxes, and finally displays contour maps of the 2D cross sections of the beam fluxes. In addition, this subsystem can carry out the 2D monitoring measurements in response to various circumstances for calibrating particle instruments.

On the other hand, the subsystem monitoring the energy and angular dispersions is now under development, which can measure spatial dependences of energy and angular dispersions on the horizontal displacement. This monitoring system consists of two axial turntables, a linear motion stage, a compact cylindrical electrostatic analyzer with a pin hole and a single-anode MCP. We have almost built a program using LabVIEW, which controls the turntables and the linear stage, sweeps the voltages applied to the electrostatic analyzer, adjusts the parameters of the beamline, and obtains count data from the MCP. The comparisons between SIMION*1 simulation results on the electrostatic analyzer and experimental results using the energetic ion beams with energies of 3 to 6keV have verified the properties of the energy and angular dispersions of the beams.

In this presentation, we will give the overview of our beamline monitoring systems and discuss the data showing the beamline characteristics in order to consider the application toward future developments of the particle instruments.

*1 : Ion and Electron Optics Simulator program

Remote sensing of the magnetic reconnection rate at the separatrix boundary

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In the Earth's magnetotail, magnetic reconnection releases stored magnetic energy and drives global magnetospheric convection. The rate at which magnetic flux is transferred from the reconnection inflow to outflow regions is determined the reconnection electric field E_r at the X-line. This so-called reconnection rate is a key parameter to evaluate the efficiency of the reconnection process and the resulting energy conversion. In this study, a remote sensing technique to obtain the peak E_r based on multi-point spacecraft observation is proposed. In this technique, the increment of the reconnected magnetic flux is estimated by integrating the in-plane magnetic field during the sequential observation of the reconnection separatrix boundary by multi-point measurements. We tested this technique by applying it to virtual observations in a two-dimensional fully kinetic particle-in-cell simulation of magnetic reconnection without a guide field, and confirmed that the estimated reconnection rate indeed agrees well with the exact rate computed at the X-line. We then applied this technique to an event observed by the Magnetospheric Multiscale (MMS) mission when crossing an energetic plasma sheet boundary layer during an intense substorm. The estimated reconnection rate for this event is $E_r \sim 15$ mV/m, which is nearly one order of magnitude higher than a typical value of magnetotail reconnection. Given that past studies have found E_r of the order 1 mV/m during weak geomagnetic activities, these results indicate that the local E_r in magnetotail reconnection may be an important parameter controlling the amplitude of geomagnetic disturbances.

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, the MMS mission consisting of four spacecraft has been conducted to elucidate the physical mechanism of magnetic field merging in the vicinity of magnetic neutral lines that exist in the central part of structures. In this study, we examine the causal relationship between electron and ion dynamics in the frame of two fluid equations.

In the initial report using MMS data, Torbert et al. [2016] evaluated the anomalous resistivity based on generalized Ohm's law. However, the verification what kind of wave is responsible for the anomalous resistivity was left as an open question.

In this study, we try to clarify this issue, adopting two-fluid equations to the two events which occurred around 2015-10-16 / 13: 07 UT and 2016-11-23/07:49UT. In the two-fluid equations, all terms other than the collision term R can be directly evaluated from observational data, so that the value of R which can be regarded as anomalous resistivity in collisionless magnetic reconnection. By comparing absolute values of electron collision term with observed wave intensities, we investigated what kind of wave is responsible for the anomalous resistivity. As a result of the analysis, the absolute value of electron collision term and the intensity of the lower hybrid waves (LHWs) were found to be highly correlated, indicating that LHWs were responsible for anomalous resistivity. Theoretically, the collision terms represent internal forces exerted between electrons and ions, so that their collision terms should be anti-correlated. Such a tendency can be seen for the first event, but not seen for the second event, which may depend on the spacecraft separations. In fact, the separations were about 13 km and 7 km for the first and second events, respectively.

磁気圏シース領域のミラー構造内磁場極小付近でのホイッスラーモード波動の観測

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Observation of whistler mode waves near the local minimum of magnetic field intensity in the magnetosheath mirror structures

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Wave-particle interactions are thought to play a crucial role in energy transfer in collisionless space plasmas in which the motion of charged particles is controlled by electromagnetic fields. However, in general, it is not easy to discriminate whether a spacecraft which observed waves had been in an effective wave generation region or outside of it at the time of observation. In the terrestrial magnetosheath, intense whistler mode waves, called 'Lion roars', are often detected around minima of semi-periodic fluctuations of magnetic field intensity. It is expected that whistler mode waves are efficiently generated near a local minimum of magnetic field intensity due to the smallest resonance velocity. We report the detailed characteristics of such whistler mode waves using the data obtained by the four MMS (Magnetospheric Multiscale) spacecraft. Using four spacecraft magnetic field data, we can derive magnetic field gradient. From limited amount of burst data of whistler mode waves with clear semi-periodic fluctuations of magnetic field intensity in the intervals of appropriate spacecraft separations (~25 or ~40 km) in Phase 1A, we found that reversals of gradient of magnetic field intensity along the magnetic field correspond to reversals of field-aligned component of Poynting flux around minima of semi-periodic fluctuations of magnetic field intensity. Such a characteristic is consistent with the idea that the whistler mode waves are efficiently generated near the local minima of magnetic field intensity and propagate toward regions of larger magnetic field intensity along the magnetic field lines on both sides. This result confirms that reversals of the field-aligned component of Poynting flux that is measurable even by a single spacecraft is useful to find good candidates of effective wave generation regions along field lines. In such regions, electron distribution functions have characteristics which are consistent with those near the centers of mirror mode structures. Since anisotropy depends on energy, simple approximation of bi-Maxwellian distributions is not usable to estimate linear growth rates at such locations. Pancake or an outer edge of butterfly electron distributions from ~100 to ~400 eV are good candidates for effective wave generation at the local minima of magnetic field intensity along field lines.

Tomography analysis of westward traveling surge observed in February, 2018

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We conducted a campaign of ground-based network observation using multi-point monochromatic imagers and the EISCAT-UHF radar in the northern Europe during February 14-17, 2018. The purpose of this campaign is to derive 3 dimensional (3D) current system of various mesoscale auroral vortex structures (e.g., spirals, westward traveling surges, and omega bands) and quantitatively estimate the ionospheric effect on the formation of them. During this period, high-speed solar wind stream (HSS) originated from coronal holes on the solar surface and associated corotating interaction region (CIR) in front of the HSS arrived in the Earth's magnetosphere and auroral activity was high. Fortunately, we observed various types of auroras during this period, such as auroral breakups, poleward expansions, westward traveling surges, omega bands, etc. In this study we focus on the westward traveling surge observed around 22:45 UT on February 16. The strategy of data analysis is as follows. First, we apply the auroral computed tomography (ACT) method to multiple auroral images for reconstructing 3D structure of the auroral emission, and then calculate height-integrated ionospheric conductivity by using the empirical atmospheric model. Second, we derive the equivalent ionospheric current from the ground-based magnetometer network data. Finally, we estimate the 3D current system (i.e., horizontal ionospheric current and field-aligned current) and horizontal distribution of the electric field by combining the ionospheric equivalent current with the conductivity. In the presentation, we will show the preliminary results of the tomography analysis.

ドリフト-アルフベン波を介した磁気圏-電離圏結合に関する理論解析

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Theoretical analysis of magnetosphere-ionosphere coupling via drift-Alfven wave

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The feedback instability is caused by the coupling of the perturbation in the ionosphere and the Alfven waves in the magnetosphere, which is a theoretical model describing the spontaneous development of the aurora arc. When a pressure gradient is formed in the magnetosphere, the dispersion relation of the Alfven waves changes due to diamagnetic drift, and the response of the magnetosphere also changes. We investigate how the electron diamagnetic drift in the magnetosphere affects the feedback instability. We extend the dispersion relation of the conventional feedback instability to include the electron diamagnetic drift in the magnetosphere, and analyze it for typical parameters of the ionosphere and the magnetosphere. As a result, it is observed that the effect of electron diamagnetic drift enhances the linear growth rate on the higher wavenumber side, and the frequency characteristics qualitatively changes.

フィードバック不安定性は、電離圏における揺動と磁気圏におけるアルフベン波の結合によって生じるものであり、オーロラアークの自発的な発達を記述する理論モデルである。磁気圏において圧力勾配が形成される場合、反磁性ドリフトによってアルフベン波の分散関係が変化し、磁気圏の応答も変化する。我々は、磁気圏における電子反磁性ドリフトがフィードバック不安定性にどのような影響を与えるかについて調べた。従来のフィードバック不安定性の分散関係を、磁気圏の電子反磁性ドリフトを含むように拡張し、電離圏と磁気圏の典型的なパラメータに対して数値解析を行った。その結果、電子反磁性ドリフトの効果により、線形成長率が高波数側で促進されること、周波数特性に質的な変化が生じることなどが観察された。

サブストームのトポロジー

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Magnetic Topology inducing the substorm

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Now, the substorm can be reproduced by the global simulation, and the mechanism of the substorm has become clear without including estimations. Although the growth phase is a strengthening of convection, flow does not reach the center of the plasma sheet, but becomes reflux toward the dayside passing through the surface of the plasma sheet. In this flow pattern, shear motion induces the quiet arc. The thinning is due to the sweeping out of magnetic flux from the inner edge of the plasma sheet by convection. It is not due to the increase in lobe pressure.

Seeing most globally, the onset is a change in convective path. This change is a state transition of convection system. After the transition, flow passes through the center of the plasma sheet, reaches the inner magnetosphere, and returns toward the dayside from there. The transient tip is observed as the dipolarization front. The state transition is a change in force balance. The BBF and the injection are parts of the change in force balance. Injection at transient stage forms a compact pressure regime which acts as the near Earth dynamo and generates an onset current system. The dipolarization corresponding to the injection is an increase of magnetic tension, but not a decrease. In the expansion phase, the ionospheric Hall current generates polarization and forms the WTS (westward traveling surge).

A large question left is the NENL formation process. What occurs if we inspect the NENL formation correctly? To do this, the null-separator structure is required. Under the northward IMF (interplanetary magnetic field), there are two nulls near the cusp of both hemispheres, forming the 2 null 2 separator structure. The deformation process from the 2 null 2 separator structure to the NENL formation is a key of substorm topology. It can be understood through three phases.

Phase 1: After a southward turning of the IMF, old 2 nulls retreat tailward, and new 2 nulls corresponding to the southward IMF are formed on the day side in the low latitude region. From new nulls, null lines extend along the frank magnetopause to old nulls.

Phase 2: The plasma sheet reconnection (also the early stage of the lobe reconnection) proceeds in the remnant tail structure formed under the northward IMF. In this structure, the retreating nulls change the configuration of the tail magnetic field to form a B_y outstanding structure in the plasma sheet just behind the dipole magnetic field. Strange to say, this deformation involves intersecting cross of magnetic fields. Similarly, retreating nulls generate magnetic field lines connecting themselves and the midnight inner magnetosphere. At the midnight reconnection point, a mixing occurs between different magnetic field lines through the B_y component. This process leads to the formation of the core B_y .

Phase 3: When B_y dominated magnetic fields of the plasma sheet is swept out downtail as the plasmoid, outer layers on the northern and southern sides contact to make the near earth tail shift to the state of the lobe reconnection. The midnight reconnection point is expanded to a line, and strong tension is activated in the x direction.

サブストームでの NENL の形成過程を調べる。サブストームのトポロジーを反並行リコネクションで理解するのは、誤りであろう。正しくは、ヌルセパレーター構造の発展により理解する必要がある。これは、以下のような3段階で理解できる。

第1段階：北向き IMF では、両半球のカusp付近にヌルがあり、2ヌル2セパレーター構造がある。IMF 南転後は、これらのヌルは反太陽方向に後退する。昼側には新たに南向き IMF に対応したヌルができる。

第2段階：旧ヌルの後退によって、テイルの磁場構造が変形される。これはヌルで磁場の結合が変えられるためである。双極子磁場のすぐ後方には、 B_y が卓越する領域ができる。この構造には、交差磁場を含む。またヌルと真夜中を結ぶ磁場ができる。プラズマシートリコネクションは、北向き IMF でできた構造の残存中で起こる。真夜中で、 B_y 成分の卓越により、磁場の繋ぎ変わりが発生する。

第3段階： B_y の卓越した構造がコア B_y となりプラズモイドとして掃き出される。その後、南北のローブ磁場が接近し、NENL の状態ができる。リコネクションは点から線に拡大する。

サブストーム時における太陽風から電離圏に至るエネルギーの流れ：MHDシミュレーション

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Energy flow from solar wind to ionosphere during substorm: Global MHD simulation

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The ultimate source of the energy involved by magnetospheric disturbances is the solar wind. When a large amount of the solar wind energy enters the magnetosphere, magnetospheric disturbances, such as a substorm, occur. Using global magnetohydrodynamics (MHD) simulation, we investigated the flow and conversion of the energy originated in the solar wind for substorms under different solar wind conditions, specified by the southward component of interplanetary magnetic field (B_s), the solar wind velocity (V_{sw}), the solar wind density (N_{sw}). We defined a solar wind effective cross-sectional area in which all the integral curves of the Poynting flux (S-curve) entering the magnetosphere pass through. About 33-88% of the magnetic energy entering the magnetosphere is converted from the solar wind kinetic energy. Since the contribution from the solar wind kinetic energy is large, the intake magnetic energy is not simply proportional to $V_{sw}B_s^2$ (Poynting flux), nor $N_{sw}V_{sw}^3$ (kinetic energy flux). The effective area decreases with B_s , V_{sw} , and N_{sw} , which also makes the relationship between the solar wind parameters and the intake magnetic energy complicated. The stored energy and the released energy in the lobe are also found to depend on the solar wind parameters, suggesting that the loading-unloading processes are also regulated by the solar wind condition. The ionospheric Joule heating rate is well correlated with the intake magnetic energy at onset, and during the substorm expansion. This can be explained by the simulation result that both the directly driven and unloading processes are regulated by the solar wind condition.

サブストーム時の静止軌道におけるプラズマ動態

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Substorm-time plasma properties at geosynchronous orbit

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Geosynchronous orbit is located near the inner edge of the plasma sheet, and is an ideal location to study the delivery of plasma sheet plasma and the coupling between the magnetosphere and ionosphere through the auroral field line. We present some case studies of plasma properties at geosynchronous orbit during substorms, using the Magnetospheric Plasma Analyzer (MPA) instruments onboard Los Alamos National Laboratory (LANL) satellites. A typical example showed that, (1) plasma density (both electrons and ions) began to increase about 20 min before the substorm onset and showed maximum value just before the onset, and then they decreased, (2) electron and ion temperatures were rather constant during the growth phase and suddenly increased at the onset, and (3) temperature anisotropy showed different manner between electrons and ions: $T_{\text{perp}}/T_{\text{para}}$ of electrons began to decrease about 20 min before the substorm onset, and $T_{\text{perp}}/T_{\text{para}}$ of ions showed sudden decrease just at the onset for a short time. These variations of plasma density, temperature, and anisotropy during substorm would be the manifestation of the global magnetospheric development and local M-I coupling process. We will show detailed plasma properties at geosynchronous orbit during substorms and discuss the substorm process around the inner edge of the plasma sheet.

Dipolarization に同期した極域電離圏の圧縮性応答

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A compressible response of auroral ionosphere induced by the dipolarization

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Key points

During a short interval (~5 min) following the dipolarization, a local accumulation of ionospheric plasmas by convection surge produced compressibility of the auroral ionosphere.

The plasma accumulation produced parallel electric fields in accordance with the Boltzmann relation by exciting ion acoustic wave.

The accumulation generated electrostatic potential of the order of 100 kV and FACs therefrom. The potential thus produced may double the atmospheric electricity.

Density accumulations in equatorward latitudes expand poleward because of their nonlinear evolution analogous to an upstream propagation of a shock in traffic flow.

Compressive ionosphere is not a mere boundary of the magnetosphere but a source region directly producing magnetospheric processes.

要点

Dipolarization の開始に続く 5 分間、極域電離圏の非圧縮性は Convection surge により破られる。

電離圏プラズマの圧縮は電離層内にイオン音波を励起する。イオン音波は磁力線沿いに平行電場を作り、また圧縮により発生する静電位 (~100 kV) は電離層起源の沿磁力線電流を生むと共に地表の空中電気を倍加する。

圧縮領域は極側後退 (Poleward Expansion) として非線形的な時間発展をする。この時間発展は交通渋滞の後方伝搬のメカニズムに類似する。

圧縮性を考慮した電離圏は単なる磁気圏境界ではなく、新しい運動を生み出す場所である。

MMS 衛星群と Geotail 衛星によるサブストーム開始の同時観測

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MMS and Geotail satellite observations of a substorm onset

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A substorm occurred at 1752 UT on August 4, 2017 with a peak of -700 nT in the AL index 6 min later. MMS and Geotail satellites were located in the plasma sheet boundary layer in the magnetotail, and were separated by 2 Re: MMS satellites were located at (X, Y) = (-18.4, 3.0) Re in aberrated GSM coordinates, and Geotail at (-16.8, 3.1) Re. These satellites were located northward from a model neutral sheet by 1.4 and 2.4 Re respectively. At 1744 UT (8 min before the substorm onset), MMS observed a magnetic dipolarization but no ion flows. In contrast, Geotail observed an ion earthward flow (150 km/s) beginning 30 s before the dipolarization. Since the MMS satellites, which were located closer to the neutral sheet, did not observe ion flows, it is inferred that there were no ion flows closer to the neutral sheet. These results suggest that magnetotail ion flow associated with substorm onsets are observed closer to the tail lobe rather than in the central plasma sheet.

AL 指数で-700nT のサブストームが 2017 年 8 月 4 日 1752UT に開始した。このとき、MMS 衛星群と Geotail 衛星は磁気圏尾部プラズマシート境界領域付近に滞在しており、両者の衛星間距離は 2 Re であった。aberrated GSM 座標系で、MMS 衛星は (X,Y)=(-18.4, 3.0) Re、Geotail 衛星は (-16.8, 3.1)Re に滞在しており、モデル neutral sheet からの距離は、それぞれ 1.4, 2.4 Re であった。

サブストーム開始の 8 分前 (1744 UT) に、MMS 衛星は、磁気双極子化を観測したが、地球向きのイオン流は観測しなかった。一方、Geotail 衛星は、磁気双極子化の 30 秒前から、地球向きイオン流 (150km/s) を観測した。このイオン流は 10keV のビームであった。Geotail 衛星よりも neutral sheet に近い MMS 衛星がイオン流を観測しなかったために、さらに深部の neutral sheet 付近で高速流が存在するとは思われない。以上の結果により、サブストーム開始に関係したプラズマ流は、プラズマシート中央部よりも、プラズマシート境界領域で先に観測されることが示唆される。

Observation Project of Sq currents by the CubeSat deployed from ISS

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Sq (Solar quiet) currents flowing in the dayside ionosphere have been considered as a significant subsequence of Mesosphere-Ionosphere-Magnetosphere coupling. In particular, it is well known that the flow pattern of Sq currents shows the north-south hemispheric asymmetry due to the different ionospheric conductivities in the winter and summer hemispheres. This indicates that the asymmetry of the potential must be kept by the energy balance between each hemisphere through the field line.

An InterHemispheric Field Aligned Current (IHFAC) was theoretically predicted by Maeda [1974] and Fukushima [1979, 1991] to interpret the north-south asymmetry in the potential pattern. Several ground magnetic observations and satellite observations suggested an existence of the IHFAC in the noon sector and both the morning and evening terminators. However, the detailed morphology of the IHFAC is not well understood yet, despite that the direct detection of the IHFAC at Low Earth Orbit (LEO) was reported in the observation by several satellites.

In order to investigate the Sq current system including the IHFAC, the in-situ observation by a CubeSat (2U size satellite emitted from ISS) is planned in collaboration with 10 national colleges which belong to National Institute of Technology (KOSEN). The fluxgate magnetometer is onboard the CubeSat to observe small perturbations of the magnetic field. After the ejection from the ISS, the CubeSat will gradually glide down to the upper atmosphere due to the strong atmospheric drag and finally burn up in it. The duration of possible observation is estimated for more than 50 days.

The CubeSat can be characterized by short development period (less than 3 years) and low cost (less than 100,000USD). We are considering an actual utilization of this extremely low-cost CubeSat to more realistic science mission. This concept enables us to conduct the multi-satellite in-situ observation in fairly low budget compared to conventional satellite missions.

Magnetosphere-ionosphere connection of storm-time Region-2 FAC and ring current: Arase and AMPERE observations

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Storm-time region-2 field-aligned currents (R2 FACs) are believed to be connected between the ring current region and the ionosphere, but this connection has not yet been clarified by simultaneous in situ observations. We quantitatively confirmed the connection of upward R2 FACs during July 16, 2017 and June 18, 2017 storm events using coordinated magnetic observations by the Arase satellite and the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) including the Iridium constellation. The upward FACs were determined by drastic changes in the azimuthal magnetic field at Arase in the off-equatorial (magnetic latitude of 23-30°) postmidnight inner magnetosphere. The magnetic latitude of the FAC projected onto the ionosphere was consistent with the ionospheric FAC observed by the AMPERE/Iridium. Using the conservation of the ratio between the current density and the total magnetic field along the field line, we showed that the current between Arase and Iridium was almost conserved, meaning that a large portion of the R2 FAC was driven in the low-latitude inner magnetosphere. We also calculated the plasma pressures of H⁺ and O⁺ ions and pressure-driven currents that are considered to be a source of storm-time R2 FACs and examined their relationship for the first event. The O⁺ pressure contributed significantly to the inner part of the total azimuthal current. The total pressure and pressure-driven current peaks were located inside and outside the FAC, respectively. A simple model calculation indicated that this spatial relationship can be explained by the day-night asymmetry of magnetic field.

MMS 衛星を用いた Pc5 波動の特性解析

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Analysis of Pc5 Wave Characteristics observed by MMS spacecraft

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The presence of high-energy charged particles is common in the geospace environment. In particular, the radiation belt is filled with the highest energy (several hundreds of keV to several tens of MeV) particles. The acceleration of radiation belt electrons is a topic of great interest in space physics (Millan and Thorne, 2007).

Ultra-Low-Frequency (ULF) waves having periods between 2 to 10 min called Pc5 waves are believed to play a role for the acceleration of radiation belt electrons. In particular, the waves which have low azimuthal wavenumber (m-number <10) are capable of accelerating particles via the drift resonance (Schulz and Lanzerotti, 1974). On the other hand, high m-number (>10) Pc5 waves (Storm-time Pc5s) that appear during geomagnetic storms may also be important (Ukhorskiy et al., 2009). Such storm-time Pc5s may be excited by plasma instabilities caused by an enhanced particle transport from the plasma sheet to the inner magnetosphere during a geomagnetic storm. The drift-mirror instability caused by pressure anisotropy is one of the most plausible candidates.

Such ULF waves likely to be generated by the drift-mirror instability are more frequently observed at $L > 8$ where the MMS (Magnetospheric Multiscale) spacecraft observations are available (Takahashi et al., 1990). With the MMS observations, we can perform both single-spacecraft and multi-spacecraft analysis methods independently. Comparisons between these methods enable us to verify the accuracy of the method based only on single-spacecraft measurement. In particular, the estimation of m-number is important in considering the resonance condition between Pc5 waves and particle. However, since observations in the inner magnetosphere are usually made with a single satellite, it is difficult to obtain reliable estimates for the m-numbers. The MMS observations are thus useful to test the applicability of single-spacecraft analysis methods in the inner magnetosphere.

In this study, we present results of such analysis for Pc5 waves observed by the MMS satellite on the dusk side in the magnetosphere on September 1, 2015. We applied the multi-spacecraft timing method for selected time intervals and obtained a wavelength of several thousands of km, westward propagation with a propagation speed of 30-40 km/s in the spacecraft frame. We also performed Minimum Variance Analysis to estimate the wave propagation directions and obtained consistent results. We will also apply other single-spacecraft methods and discuss the accuracy by comparing results obtained with different methods.

地球周辺の宇宙空間には、エネルギーの高いプラズマ粒子が飛び交う領域が存在する。特に数百 keV から数十 MeV の、最も高いエネルギー帯のプラズマ粒子で満たされている領域は放射線帯と呼ばれ、放射線帯の電子の加速現象は宇宙空間物理学の重要な研究課題である (Millan and Thorne, 2007)。

この電子の加速機構の候補として注目されているのが、Pc5 波動と呼ばれる、2~10 分の周期を持つ ULF 波動である。特に経度方向の波数 (m-number) が低い波動 ($m < 10$) は、ドリフト共鳴によって相対論的電子加速に重要な役割を果たすと議論されてきた (Schulz and Lanzerotti, 1974)。その一方で、磁気嵐時に発生するような高い m-number (> 10) の Pc5 波動 (storm-time Pc5) も、放射線帯の粒子加速に寄与する可能性が指摘されている (Ukhorskiy et al., 2009)。このような storm-time Pc5 は、磁気嵐時にプラズマシートから内部磁気圏に輸送されるプラズマ粒子が引き起こすプラズマ不安定によって励起されると考えられており、温度異方性によって起こるドリフトミラー不安定はその有力な候補である。

ドリフトミラー不安定で励起されたと考えられる ULF 波動は、MMS (Magnetospheric Multiscale) 衛星の周回軌道 ($L > 8$) においてより頻繁に観測されている (Takahashi et al., 1990)。MMS 衛星を用いることで、複数衛星を用いた解析手法 (Timing Method など) と、単一衛星のデータのみを用いた解析手法の両者を用い、単一衛星のみを用いた解析手法の精度の検証が可能である。特に Pc5 波動と粒子の共鳴条件を考えるにあたっては m-number の推定が重要であるが、内部磁気圏の観測では通常は単一衛星しか用いることができないため、その精度検証が困難である。そのため、単一衛星を用いた m-number の推定手法の精度を、独立な手法によって検証することは内部磁気圏への応用においても重要である。

本研究では、2015 年 9 月 1 日に磁気圏の夕方側で MMS 衛星によって観測された Pc5 波動について解析を行った。Timing Method による解析を用いていくつかの時間帯において波長と伝播方向、伝播速度を求めた。その結果、波長は数千 km、伝播方向は西向きで、衛星静止系での伝播速度は 30-40km/s 程度であった。これは過去の研究と一致する。さらに、4 衛星それぞれのデータを用いて Minimum Variance Analysis を用いて伝播方向の推定を行った。その結果、Timing Method から得られた伝播方向と一致することを確認した。発表では上記の結果に加えて、その他の解析手法の適用結果を示し、各手法の精度を検討する。

Effects of the inclination and rotation of Earth's magnetic axis on the near-Earth plasma environment in global MHD model

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Recently, we have shown that the ionospheric Hall conductance distribution, owing to the polarization field generated by its nonuniformity, largely control the magnetospheric configuration and dynamics by using a global MHD model. The effects of the ionospheric conductance on the magnetosphere were also reported by previous studies based on other global models; for example, the current-voltage relationship in the solar wind-magnetosphere-ionosphere [Fedder and Lyon, 1987] and the plasma pressure distribution in the near-Earth region [Ridley et al., 2004]. These studies indicate that the ionospheric conductance is one of the most important settings in the global models to accurately simulate the magnetosphere.

On the other hand, in the development/improvement of the global MHD model in NICT, which was originally developed by Tanaka [1994] and Tanaka et al. [2010], introducing the inclination and rotation of Earth's magnetic axis with respect to the rotation axis has been remained as one of the most difficult problems. In other words, in the present model, the precession between the magnetic axis and the rotation axis is not included. This means that the simulated magnetosphere will show a different structure and temporal development than the actual magnetosphere, particularly during the summer and winter seasons.

We, for the first time, equivalently introduce the precession by rotating the background conductance distribution due to solar illumination (i.e., depending on the geographic coordinate) with respect to the geomagnetic coordinate. (Improvement of the conductance setting in the auroral region is the next challenge.) In this paper, we will show how the near-Earth plasma environment is changed by this improvement.

Axisymmetric conductivities of Jupiter's middle- and low-latitude ionosphere

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Ionospheric Hall and Pedersen conductivities are important parameters in determining the electric potential distribution and plasma convection in a magnetosphere-ionosphere system. At Jupiter, meteoric ions generated by meteoroid ablation are expected to play a major role in the ionospheric conductivities [e.g., Cloutier et al., 1978]. Hall and Pedersen conductivities are expected to be axisymmetric at Jupiter due to the long lifetime of meteoric ions. This study aims to evaluate the modification of the potential distribution and plasma convection in the inner magnetosphere caused by the axisymmetric ionospheric conductivities at Jupiter.

There have been observational constraints on the effect of the ionospheric conductivities to the plasma convection in the inner magnetosphere. Observations by the Hisaki satellite revealed that the brightness intensity of the Io plasma torus changed asymmetrically between the dawn and the dusk sides and this change coincided with a rapid increase in the solar wind dynamic pressure. Such change can be explained by the existence of a dawn-to-dusk electric field of $\sim 4-9$ [mV/m] around Io's orbit [Murakami et al., 2016]. The dawn-to-dusk electric field can be generated by the dawn-to-dusk asymmetry of the ionospheric electric potential caused by the Region 2 like field-aligned current.

In order to evaluate the contributions of meteoric ions to the Jovian ionospheric conductivities and dawn-to-dusk electric field in the inner magnetosphere, we developed a 3-D photochemical model and a 2-D ionospheric potential solver. Our 3-D photochemical model includes chemical reactions taken from Kim et al. [1994, 2001], vertical thermal diffusion of ions, mass deposition rate of meteoric atoms and ions by meteoroid ablation, and ionization by precipitating electrons. The input parameters of field-aligned current are the Region 2 like current with reference to Khurana [2001] and axisymmetric Hill current. Our 2-D ionospheric potential solver was developed using the methods in Nakamizo et al. [2012]. First, we calculated the global distribution of ionospheric conductivities using ion and electron density profiles acquired from the photochemical model. Second, we calculated the ionospheric potential distribution and the resulting dawn-to-dusk electric field in the inner magnetosphere.

Our simulation results showed that the largest contributions to the Hall and Pedersen conductivities occur in the meteoric ion layer, and the conductivities are axisymmetric in the middle and low latitudes. Meteoric ions dominate the ion densities between 300 km and 400 km altitudes. The peak electron number density is $\sim 3 \times 10^{11}$ [m^{-3}], which located at the meteoric ion layer around 370 km, and $\sim 1 \times 10^{11}$ [m^{-3}] at the H^+ peak around 1000 km. We confirmed that electron density profile is almost constant at any local time due to the long lifetime of H^+ and meteoric ions. We confirmed that the ionospheric conductivities reach their maxima at the meteoric ion layer, and the height-integrated Hall and Pedersen conductivities become axisymmetric at middle and low latitudes at Jupiter. At high latitudes, the conductivities indicate the dawn-to-dusk asymmetry associated with the Region 2 like field-aligned current.

We will discuss the modification of the potential distribution in the ionosphere and the dawn-to-dusk electric field in the inner magnetosphere at Jupiter, due to the axisymmetric conductivities at the middle and low latitudes caused by meteoric ions and the dawn-to-dusk asymmetric ionospheric conductivities at high latitude caused by the Region 2 like current. Furthermore, comparison between our results and the Hisaki observations will be also discussed in the presentation.

FLRの自動同定とそれを用いた磁気嵐中の磁気圏プラズマ密度の解析

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Automatic identification of FLR and analysis of the magnetospheric plasma density during magnetic storms

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The plasma density in the magnetosphere is a fundamental quantity of the magnetosphere, and it is important for understanding phenomena occurring in the magnetosphere such as magnetic storms. The plasma density can be directly observed by satellites, but their simultaneous spatial coverage is limited. On the other hand, ground magnetometers densely cover the Earth surface, and from their data one can estimate (by a method described below) and make two-dimensional snapshots of the magnetospheric equatorial density.

In our research, we estimate the magnetospheric plasma density by using the FLR (Field-Line Resonance). The FLR fluctuates the H-component of the ground magnetic field in a unique manner; by using this feature, the FLR is identified and the FLR frequency is determined by applying the cross-phase and the amplitude-ratio methods to the data from two magnetometers closely placed in the north-south direction. Because there are several meridional magnetometer chains in Canada, it is possible to make detailed two-dimensional snapshots of the magnetospheric equatorial density in the area to which Canada is mapped along field lines.

In the conventional approach, the FLR has been visually identified in the plots of the cross phase and the amplitude ratio, but it takes considerable time and efforts. Thus, in our research, we have improved the automatic-identification program which hired a new algorithm [Kitagawa, master thesis], applied it to the data of the Halloween event (2003/10/28~11/1) for which the plasma density was estimated in other papers, and confirmed the preciseness of our program.

As a case study, we have analyzed a magnetic storm (2011/9/26~10/1) by using the data from Canada and estimated the plasma density. As a result, we have confirmed that the plasma density increased in the main phase of this storm. In relation to this, we are investigating the position of the plasmopause during this storm. Considering this and other features of this storm, we will clarify the cause of the increase of plasma density and report the result.

磁気圏プラズマ密度は磁気圏の基本的物理量であり、磁気嵐など磁気圏で生じる現象を理解する上で重要である。磁気圏プラズマ密度の観測法としては、衛星で直接観測する方法と地上磁場観測から間接的に推定する方法がある。衛星直接観測では精確な密度値が得られるが、同時観測している磁気圏観測衛星の数は少なく、磁気圏広域をカバーする事は出来ない。一方地上磁場観測からの推定は、精度は衛星より劣るが、地上に多数の磁力計が存在するので磁気圏の広い領域を同時観測できる。本研究では、FLR (Field-Line Resonance) 現象を用いて地球磁気圏のプラズマ密度を推定する。FLR は地上磁場 H 成分を特有のパターンで変動させる。この性質を用い、同経度上で南北に近い2つの磁力計のデータに二点法と呼ばれる方法 (2 観測点の H 成分の振幅比と位相差を用いる) を適用することにより、FLR を同定しその周波数を求めることができる。カナダには複数の観測点 meridian chains が存在するので、順次二点法を適用することで、磁気圏赤道面プラズマ密度の2次元分布を推定できる。

従来は、二点法解析結果を目で見て確認して FLR を同定していたが、かなりの手間がかかるので、本研究では、新しい方法論に基づく FLR 自動同定プログラム [北川、修士論文] を改良し、ハロウィンイベント (2003/10/28~11/1、磁気嵐中のプラズマ密度が他論文により既知) に適用・比較して精度を確かめた上で使用した。

Case study として、2011/9/26~10/1 の磁気嵐イベントについてカナダのデータを解析し、プラズマ密度の推定を行った。その結果、このイベントでは主相中にプラズマ密度が増加していることを発見した。それに関連して、現在は磁気嵐中のプラズマポーズの位置についても調査しており、その結果に他の観測も併せて総合的にプラズマ密度の増加の原因を解明し、その結果を報告する。

Experimental observations of geomagnetic field with magneto-impedance sensor

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In geomagnetism or space physics, magnetic field variations are usually measured with the fluxgate magnetometer. This instrument has a high resolution of the order of 0.1 nT or less, which is enough to detect various geomagnetic phenomena, such as geomagnetic pulsations, Sq variations, and geomagnetic storms. However, since one fluxgate magnetometer generally costs a few tens of thousand US dollars, it is difficult to deploy network observations with a limited amount of research grants.

Magneto-impedance (MI) effect was discovered about 25 years ago and a micro-size magnetic sensor that utilizes this effect becomes commercially available. It costs approximately 500 US dollars for a single-axis sensor. We made some modifications to the commercially available MI sensors as they can cover the range of the geomagnetic field ($\pm 50,000$ nT). For the period of March 30 to April 27, 2018, we conducted experimental observations of geomagnetic field variations with the MI sensors at Mineyama observation site, which is located about 100 km north-west of Kyoto. Data obtained with the MI sensors were compared with those from the fluxgate magnetometer that have been working at the site. Results showed that the MI sensor recorded geomagnetic variations with amplitudes of ~ 1 nT that were also detected with the fluxgate magnetometer. This suggests that MI sensors are useful for researches in geomagnetism or space physics, although they are much less expensive than fluxgate magnetometers. In presentation, we will display observation data from both the MI sensors and the fluxgate magnetometers at Mineyama. Future plans will be also discussed.

Swarm 衛星を用いた北半球極冠域の沿磁力線電流の統計解析

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Statistical analysis of field-aligned currents in the northern polar cap region with Swarm satellites

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One of the dynamical phenomena occurring in the polar cap is so-called polar cap arcs. Polar cap arcs are generally aligned with the noon-midnight meridian; thus, they are sometimes called Sun-aligned arcs. It is well known that the dawn-dusk motion of polar cap arcs depends on the By component of interplanetary magnetic field (IMF). However, the details of their source region and generation mechanism have not yet been clarified. To discuss such unresolved problems, it is necessary to elucidate the M-I coupling process occurring 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 downward from the magnetosphere into the ionosphere along the magnetic field line and then upward FAC flows from the ionosphere to the magnetosphere. By measuring FAC, it is possible to understand the M-I coupling process above polar cap arcs. 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 arcs does not change so much in the direction along the arcs. However, when the horizontal structure of FAC and the satellite orbit are close to parallel, the assumption is often invalid and it would be difficult possible to measure the FAC structure accurately.

To resolve this problem, the geomagnetic observation satellite Swarm has been conducting formation flight observation with multiple satellites. It consists of Swarm A, B, and C, and among them Swarm A and C fly nearly parallel on the almost same orbit. Therefore, it is possible to estimate FAC using dual satellites. This dual-satellite method makes it possible to estimate FAC regardless of the geometric relationship between the FAC structure and the satellite orbit. In this study, we conducted a statistical analysis using dual-satellite method FAC data, and examined the dependence of polar cap FAC characteristics on IMF and season. First, we extracted 4335 signatures of upward FAC in the polar cap, whose current density is larger than 0.5 Am^{-8} . Many of them were located on the dayside, which are FAC in the cusp. Since our focus is on FACs associated with polar cap arcs in the central polar cap, such dayside FACs was excluded from the statistics. As a result, the total number of FAC signatures is 1808. We confirmed that there are the dependences of FAC occurrence on both the IMF Bz and By. In addition, it was also found that the occurrence of high FAC region depends on season. In the presentation, we will discuss the origin of these dependences on IMF and season in detail.

オーロラオーバルより極側の高緯度地域を極冠と呼ぶ。極冠で発生する現象のひとつに極冠オーロラがある。極冠オーロラは太陽方向に伸びた構造をしており、弱い赤色の発光をするという特徴がある。また、Interplanetary Magnetic Field (IMF) By が正の時に夕方方向、負の時に朝側方向に運動することが知られている。しかし、そのソース領域や発生メカニズムの詳細は明らかになっていない。極冠オーロラが発生している領域では電離圏から磁気圏に向けて磁力線に沿って流れるFAC (Field-Aligned Current) が存在する。このFACを測定することでオーロラ近傍のM-I Couplingの時空間変動や、磁気圏側のソース領域に関する情報を得ることができる。FACは従来、DMSPやCHAMP等の単機衛星による磁場観測の時間変化を空間変化と見なすことで、その回転を計算することによって推定が行われてきた。この時、回転を計算する場の空間構造がアークに沿って大きく変化しないことが暗に仮定されている。しかし、衛星軌道とFACの水平構造の幾何学的関係が平行に近くなると、この仮定が破れ、極冠オーロラ近傍のFACの空間構造を正しく観測できないと考えられる。

この問題点を克服するために、地磁気観測衛星Swarmは複数機による編隊飛行観測を行っている。Swarm A, B, Cの3機で構成されており、このうちAとCは同一軌道をほぼ平行に飛行することで、2機を用いたFAC推定が可能になっている。この推定方法ではFAC構造と衛星軌道の関係によらず、どのような条件でもFACの推定が可能である。これにより、従来観測できなかった極冠オーロラの観測事例を含めたFACの統計解析が可能になる。本研究では、この2機を用いて推定された極冠域FACについて、2015年-2017年の3年間に取得されたデータを統計的に解析し、北半球極冠域FACの発生分布と強度のIMF、季節に対する依存性について考察する。

まず、磁気緯度80度以上かつ、FAC密度の絶対値 0.5 Am^{-8} 以上の条件のもと上向きFACのピークを検出した結果、4335点のピークが検出された。これらの多くは昼間側に位置しており、平均のFAC密度は、夜側ではおおよそ 1.0 Am^{-8} 前後であるのに対し、昼間側では 1.5 Am^{-8} 以上の高い値を取ることが明らかになった。この昼間側の高密度FACはカスプ由来であると考えられ、本研究では極冠オーロラ由来のFACに注目するため8-16 MLTのデータは除外した。昼間側のデータを除外した結果、総検出数は1808点となった。次にIMFについて依存を確認した結果、先行研究で知られているように、IMF Bzが正の時に、極冠域で上向きFACの発生が顕著であることが分かった。また、極冠オーロラの発生頻度に大きく影響しないと考えられるIMF Byについても、その値が正の時に上向きFACの領域が高い頻度で現れることが明

らかになった。次に季節に対する依存性を確認したところ、発生数は5月を極大、12月を極小とする変化が見られた。5月の発生数は12月の発生数の約10倍となっており、これは日照域での電離圏電気伝導度が上昇しているために、FACの電流密度が大きくなったためと考えられる。発表では、以上のIMFと季節に対する極冠域FAC強度の依存性の要因について議論を行う。

サブストームオンセット後に励起されるPc4脈動とオーロラストリーマの動態解明に向けて

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The THEMIS reveal morphology of Pc4 pulsations and auroral streamer excited after substorm onset

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It is well known that Pi2 pulsations are excited on substorm onset. However, it is not yet clarified about morphology of Pc4 pulsations frequently observed during expansion phase to recovery phase of substorm. Pc4 is expected to relate earthward plasma flow due to the depolarization of earth's magnetic field and associated vortex generation. Therefore, it would become very important indicator for investigation of magnetospheric dynamics after substorm onset.

In this study, by using the magnetic data obtained from ETS-VIII synchronous orbit satellite and the MAGDAS/CPMN ground stations (210 meridian chain), we found that the Pi2 globally occurs after substorm onset and rapidly disappeared with several periods, while Pc4 continues during recovery phase but only at the nightside high latitudinal region (above sub aurora region). Furthermore, by using THEMIS satellites, it is found that Pi2 can be captured at the dayside magnetosphere, while Pc4 is observed only at the nightside magnetosphere with same waveform on the ground.

These results suggest that Pi2 propagate from nightside to dayside magnetosphere as a compressional wave, while Pc4 is excited as shear Alfvén wave at the nightside magnetosphere and propagate to the high latitude ionosphere.

In this presentation, we will discuss about detail of the above results and, report an initial result obtained from comparative study between aurora emission and Pc4 pulsations by using electromagnetic data from THEMIS satellites, aurora activity from THEMIS all sky camera, THEMIS magnetic field data, and global MAGDAS magnetic field data.

サブストームオンセット時に Pi2 脈動が励起されることは良く知られているが、オンセットから爆発相、回復相にかけてしばしば観測される Pc4 脈動についてはその動態はあきらかにされていない。Pc4 脈動はその継続性から、オンセット後の地球磁場の双極子化に伴う地球向きプラズマフロー及び、それに伴う渦形成と関連していることが期待され、サブストームオンセット後の磁気圏の動力学を観測的に精査する上で非常に重要である。

我々は MAGDAS/CPMN 地上磁場観測網 (経度 210 度 meridian chain) の及び、ETS-VIII 衛星の磁場データを用いて、サブストームのオンセットに伴い、Pi2 脈動が全球的に観測された後、サブオーロラ帯より低緯度側では速やかに振動が収まるが、それより高緯度領域においては、爆発層から回復相にかけて Pc4 脈動が継続的に励起されるという結果を見いだした。また、多点衛星である THEMIS 衛星の磁場データと MAGDAS/CPMN の地上磁場データを用いてサブストームの爆発層から回復相にかけての Pc4 の発現特性を調べ、Pi2 はサブストームオンセットと同時に夜側の地上、衛星の全地点で観測されるとともに、Pc4 は衛星観測では夜側サブストームの爆発層から回復相にかけて観測され、昼側は観測されないこと、地上では高緯度においてのみ衛星と同様の波が観測されることを確認した。以上のことから、Pi2 は圧縮波により磁気圏では夜側から昼間側に向けて拡がるのに対して、Pc4 は夜側の高緯度領域に局在し、磁力線に沿った Alfvén 波として地上に伝播していることが予測される。

本研究では、以上の結果の詳細について議論するとともに、磁気圏-電離圏結合系におけるサブストーム爆発層から回復層にかけてのオーロラの動態とその三次元構造解明を目的として、THEMIS 衛星と地上の全天カメラ、地上磁場データの同時観測データを用いた、Pc4 脈動の発現特性とオーロラ動態を比較研究の初期結果について報告する予定である。

Extraction of the two-dimensional flow pattern and fluctuations from a sequence of auroral images

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Since aurorae are associated with various magnetospheric processes, aurora observation is a promising way to monitor the magnetosphere. Nowadays, routine aurora imaging observations with high time resolution are conducted at many observation sites, and aurora imaging data have become widely available.

We are developing a technique for obtaining physical quantities from aurora image data. In our technique, the variations of an aurora are decomposed into a persistent component (no blink) and residual fluctuations. The persistent component shows drift motion, which is possibly associated with the large-scale magnetospheric electric field. The residual fluctuations are related with the pulsating aurorae, which would be related with magnetospheric plasma waves. The persistent component and the flow pattern of its drift motion can be extracted by using an approximation of the Kalman filter algorithm. Since each auroral image which consists of a large number of pixels is high-dimensional data, it requires high computational cost to apply the standard Kalman filter algorithm. In order to reduce the computational cost, we represent the drift velocity distribution on an image by a stream function expanded using 36 basis functions. In addition, each uncertainty covariance matrix is approximated by a diagonal matrix. These approximations enable us to obtain an efficient algorithm for estimating the persistent component and the flow pattern. We will describe the outline of the proposed method and demonstrate some results.

ISS - IMAP VISI で撮像された孤立型プロトンオーロラの移動特性: マルチイベント解析

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Motion of isolated proton aurora observed by ISS-IMAP VISI: multi-event analyses

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Isolated proton aurora (IPA) is a localized region of proton precipitation sometimes observed at latitudes lower than the main aurora oval. The generation mechanism of IPA is based on pitch angle scattering of protons by electromagnetic ion cyclotron (EMIC) waves through the wave-particle interactions at the magnetic equator. Thus, IPA has temporal and spatial correlations with Pc 1 observed on the ground. However, large-scale spatial characteristics and dynamic properties of IPA are still unclear because of limited number of observations from space. In this study, we use auroral images taken by ISS-IMAP VISI on International Space Station (ISS) obtained during three years from September 2012 to August 2015. Six cases of IPA, some of which continued to be observed for consecutive multiple paths, are found.

During the first event on August 20, 2015, IPA was observed during one single path at ~ 60 MLAT. The ground-based induction magnetometer observation at Magadan in the northern hemisphere (similar local time) showed an intense activity of Pc1 wave (0.7 - 1 Hz) during the period of this IPA. During the second case on 24 July 2015, IPA was observed during four continuous paths at ~ 62 MLAT. An enhancement of Pc1 wave was detected at Magadan slightly before the IPA interval. This slight discrepancy is probably due to the hemispheric and longitudinal difference in the EMIC activity. In this case, IPA moved from the nightside to the morning side and the eastward speed ~ 320 m/s. During the third event on August 18, 2015, IPA was observed for two continuous paths at ~ 62 MLAT. The Pc1 wave was high active at around 1 Hz from 16 UT to 17 UT at Magadan. In this case, the IPA moved westward from the post-midnight to pre-midnight at a speed of 220 m/s. The longitudinal motion of IPAs seen during the second and third events could be associated with the background $E \times B$ drift by co-rotation electric field of relatively colder plasma or convection electric field in the magnetosphere. The difference (i.e., eastward or westward) in the direction of IPA motion will be discussed in comparison with the ionospheric plasma drift measurements by SuperDARN. In the presentation, some initial analyses of data from MAXI-RBM, which measures high-energy electron precipitation, will also be demonstrated to discuss simultaneous precipitation of radiation belt electrons in the region of IPA.

孤立型プロトンオーロラ (IPA) はオーロラオーバルより低緯度に見られる局所的なプロトンオーロラである。磁気赤道面付近で EMIC 波動との相互作用によって陽子がピッチ角散乱を受け、地球の超高層大気に降り込むことで生成されると考えられている。EMIC 波動は地上で観測することができる。これまでの研究によって、IPA と Pc1 の発生には時間・空間的な相関があることが分かっている。しかし、IPA は発光強度が低いため観測事例が多いとは言えないため、その広域空間特性や移動特性などの解明が進んでいない。また、IPA の領域には、MeV オーダーのエネルギーを持つ相対論的電子が降下していることも観測的に確認されており、放射線帯電子の消失過程を理解するうえでも、その空間構造を広域に観測することが求められている。本研究では、国際宇宙ステーション (ISS) に搭載された可視分光撮像装置 (ISS-IMAP VISI) を用いて撮像された 2012 年 9 月から 2015 年 8 月までの 3 年間のデータを用いた。VISI の観測波長は 630nm, 650nm, 762nm およびその背景光である。ISS の軌道傾斜角が 51.6 度であるために、IPA を含めオーロラを観測できる機会が必ずしも多いわけではないが、3 年間のデータから 6 例の IPA を抽出した。6 例全てが南半球での観測となっているが、これは地理極と磁気極のオフセットが南半球側で大きいため、ISS が磁気的な高緯度まで飛翔することができることによるものである。これらの事例の中には、複数のパスに渡って観測されるものもあり、構造の移動特性を解析することが可能となっている。今回は単一パスで観測された事例と複数パスで観測された事例の計 3 つの事例について報告を行う。

2015 年 8 月 20 日に、磁気緯度 -60 度、04MLT で IPA が観測された。空間スケールは東西に 600km 程度、南北に 100km 程度で東西方向にやや伸びたパッチ状の空間構造を示していた。この時間帯に、経度が近い北半球の Magadan では、強い強度の Pc1 が観測されており、EMIC 波動によるピッチ角散乱との関連性が示唆される。2015 年 6 月 24 日の事例では、磁気緯度 -60 度付近で、23 MLT から 03 MLT にかけて 4 つの連続パスで観測されていた。空間スケールは東西に 280km 程度、南北に 160km 程度で東西方向にやや伸びたパッチ状の空間構造を示していた。このとき、北半球の Magadan で観測された Pc 1 は 18 UT 頃は 1.1 Hz 付近で強度が大きくなっているが、それ以降は強度が大きくなっておらず、半球および経度が少し異なるために 1 対 1 の対応が見られなかったものと考えられる。事例では、IPA は少しずつ形状を変えながら、夜側から朝側に向けて移動していた。経度方向の移動速度は 2 つ目と 3 つ目のパスの間でおおよそ

160 m/s であり、3 パス目から 4 パス目の間でおおよそ 320 m/s 程度であった。2015 年 8 月 18 日に観測された事例は、磁気緯度 -62 度付近で、02 MLT から 03 MLT にかけて 2 つの連続パスで観測されていた。空間スケールは東西に 400km 程度、南北に 100km 程度で東西方向にやや伸びたパッチ状の空間構造を示していた。北半球の Magadan で観測された Pc 1 は IPA が観測されている 16 UT から 17 UT にかけて 1 Hz 付近で強度が強くなっており、EMIC 波動との関連性が示唆される。この事例は、IPA は 2015 年 6 月 24 日の事例と異なり朝側から夜側に向かって移動するという特徴を持っていた。経度方向の移動速度はおおよそ 220 m/s であった。IPA の経度方向の移動は、磁気圏プラズマの共回転電場もしくは対流電場による ExB ドリフトを反映しているものと考えられる。Super DARN レーダー網や DMSP 衛星のドリフトメーターによって得られるデータと比較することで、IPA の移動速度と背景対流との関連性を調べ、上記の 2 例の IPA の伝搬方向の違いについて議論する。また、ISS に搭載されている MAXI-RBM による放射線帯電子降下の同時観測データについても現在比較をスタートさせており、その初期結果を報告する予定である。

動くメソスケールカuspオーロラに伴うプラズマ速度プロファイル

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Plasma flow profiles associated with moving mesoscale cusp auroras

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A cusp mesoscale aurora form whose motion has a poleward component is thought to be accompanied with mesoscale twin-vortex plasma flow, and the plasma flow is likely to be relatively fast in the vicinity of the region where the two vortices contact with each other. Since the intense aurora tends to occur in the area of one vortex, which is associated with upward field aligned currents, relatively fast flow would be present near the boundary of the aurora. To understand detailed relationships between relatively fast flow and the moving mesoscale aurora in the cusp, we examined data from simultaneous observations of an all sky imager and the EISCAT Svalbard Radar (ESR) located in Longyearbyen, Svalbard. Results of statistical analyses suggest that the location of the fast plasma flow does not always fit in the above-mentioned picture. We discuss the result in terms of the shape of the mesoscale aurora and the direction of the background plasma flow.

カusp領域には、極向きの速度成分をもって移動するメソスケールのオーロラがしばしば発生する。このオーロラが強く光っている領域には、上向きの沿磁力線電流を伴うプラズマの渦が存在し、その渦にはペアをなす反対向きの回転の渦が隣接して、2つの渦がともに動いていると考えられている。この twin-vortex モデルでは、2つの渦が向かい合う部分でプラズマの流れが速くなると考えられており (Taguchi et al., 2015)、1つの渦とオーロラが重なるなら、オーロラの水平方向の広がり境界付近でプラズマの流れが速くなっていることが期待される。本研究では、プラズマの流れが速くなっている部分は、実際にオーロラの水平方向の広がり境界付近に位置しているのか、また、どのような時にオーロラの境界のどの部分（動くオーロラの前側か後側か）に生じているのかを明らかにする。

この目的のため、本研究ではスバルバル諸島のオーロライメージャーと EISCAT Svalbard Radar (ESR) による同時観測データを解析した。630 nm の波長で得られたメソスケールのカuspオーロラの画像を調べ、比較的孤立したオーロラが、ESR の固定アンテナのビームの方向を通過している事例を2012年から2015年の冬季(12月と1月)の観測データから取り上げた。ESR で得られる量のひとつであるイオン温度は、プラズマの流れの速さを反映する。ESR のイオン温度のデータをもとに、レーダーの視野を切って移動していくメソスケールのオーロラのどの部分でプラズマの流れが相対的に速くなっているのかを調べた。オーロラの形状と背景流の特徴に伴って、プラズマの流れが速くなっている部分がどのように位置を変えるのかについて報告する。

多点衛星観測データ解析における最小二乗法再考

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Revisiting minimum variance projection for multi-spacecraft data analysis

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Minimum variance projection is a powerful tool in the multi-spacecraft data analysis. Theoretical construction of the minimum variance projection is revisited and discussed in view of the maximum likelihood for a Gaussian form by using the data covariance as a proxy of the noise covariance in the measurement. An error estimate is suggested, too. The minimum variance projection can be extended to decompose the measured multi-spacecraft data into different components or shapes.

最小二乗法は磁気圏の多点衛星観測のデータ解析において威力を発揮するデータ解析手法であり、とりわけ波動解析に広く使われている。最小二乗法の理論的な背景を尤度関数の視点から見直すことにより、最小二乗法ではデータ解析において測定値の共分散をノイズの共分散の代理として使っていることが分かる。最尤法の視点からだと最小二乗法の誤差（もしくは信頼区間）評価も可能になる。最小二乗法と最尤法を組み合わせることにより、観測データを複数の異なる波形に分解することも可能になる。

カスプの赤道側境界に沿うオーロラ増光スポット間の特性距離

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Characteristic distance between auroral brightening spots along the equatorward boundary of the cusp

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Mesoscale auroral brightenings observed near the equatorward boundary of the cusp are thought to be the ionospheric signature of the beginning of intermittent reconnection on the dayside magnetopause, i.e., a flux transfer event (FTE). Multiple brightening spots often appear along the equatorward boundary of the cusp. Our understanding of the location of the multiple brightening spots is lacking. In this study, we clarify the characteristic distance between the multiple brightening spots along the equatorward boundary of the cusp. We examined 630-nm aurora data obtained by a ground-based all-sky imager at Longyearbyen, Svalbard during seven winter seasons. Results of statistical analyses show that there exists a characteristic distance between two neighboring spots, which is 0.2 to 0.5 hour in MLT during southward IMF. Results also show that there are several intervals when the distance is kept at ~0.4 hour in MLT. We discuss whether these results simply reflect the occurrence of the FTE or suggest some additional processes of electron precipitation, which are not related to the FTE.

カスプの赤道側境界付近に現れるメソスケールのオーロラの増光は、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を引き起こしている。この種のオーロラの増光の中には、大きく位置を変えずに、その場で減衰してしまうものもあるが、北向き IMF 時を除く多くの状況のもとでは、オーロラの増光領域は極向き速度成分をもって移動していく。このようなオーロラは、特定の経度で観測した場合には、平均で4分程度の発生間隔をもつことがわかっている。カスプは通常、MLTで4時間程度の幅をもち、その幅に比べると1つのメソスケールのオーロラ増光の経度方向の長さは十分短く、カスプの赤道側境界に沿う広い範囲で複数のオーロラ増光スポットが次々と現れる場合もある。また、これらのスポットが prenoon 側と postnoon 側のどちらに現れやすいのかについて、IMFの東西成分が関わっていることもこれまでの研究からわかっている。しかしながら、複数のオーロラ増光スポットが次々と現れる際に、それらのMLT方向の間隔に関わる性質はほとんど明らかになっていない。本研究では、オーロラ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、昼側カスプの赤道側境界に沿うオーロラ増光スポットの間の距離に関わる性質を明らかにする。

ロングイヤービエンに設置されている全天イメージャーによって取得された630 nmのオーロラデータを解析した。これまでの研究により、このデータを使ってカスプの赤道側の緯度が概ね決められることがわかっている。このことをふまえた一定の基準を導入し、2011年から2017の7年間の冬季シーズン(12月と1月)の観測データから、カスプの赤道側境界付近に現れるメソスケール増光スポットを自動検出した。IMFが南向きで比較的安定している場合に注目すると、スポット間の距離は0.2 - 0.5 MLTが多い。また、約0.4 MLTの距離が卓越する期間もあり、増光スポットは、経度方向にランダムな間隔で発生しているわけではないことがわかる。そのような特徴的な距離について、増光スポットが連発する時の時間差の観点から分析した結果も報告する。さらに、それらの結果をもとに、オーロラ増光スポットの発生は、マグネトポーズのFlux transfer eventの発生と完全に結びつけられるのか、あるいは、それ以外のプロセスも実質的に関わっているのかについて考察する。

Dependence of the ion-to-electron temperature ratio on flow speed in the plasma sheet

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Plasma in the Earth's magnetosphere are heated up to 1-10 keV and stored in the plasma sheet in the magnetotail. The magnetotail plasma can be accelerated by magnetic reconnection, which occurs to release the magnetic field energy. The accelerated plasma are transported both earthward and tailward as fast flows with a speed of several hundred kilometers per second or faster. It has been reported that the properties of plasma sheet plasma such as ion temperature, electron temperature, and the ion-to-electron temperature ratio depend on fast flow conditions and spatially vary [Kaufmann et al., 2005, Wang et al., 2012]. However, it is not well understood how transport and acceleration of the magnetotail plasma depend on mass and/or charge.

In this study, using plasma data obtained from the FPI instrument on board MMS, we first examine the flow speed dependence of the ion-to-electron temperature ratio in the plasma sheet. We use the data for a period from June to August 2017, when MMS was flying in the near-equatorial magnetotail in the region of $X_{GSM} < -25R_E$ and $-15R_E < Y_{GSM} < 15R_E$. We divide observations into three different groups according to flow speed: slow flow event ($|V_{ion}| < 100$ km/s), middle flow event (100 km/s $< |V_{ion}| < 400$ km/s), and fast flow event ($|V_{ion}| > 400$ km/s). We then investigate the occurrence distributions of the plasma temperatures and the ion-to-electron temperature ratio for each group.

The results show that both ion and electron temperatures increase with increasing flow speed. On the other hand, the occurrence distribution of the ion-to-electron temperature ratio does not differ between the three groups. We also investigate differences between earthward flow and tailward flow. For earthward flow events, the trend is similar to the above-mentioned results. For tailward events, ion temperature and the ion-to-electron temperature ratio of fast flow events show larger value than those of any other flow events. We also examine how the ion-to-electron temperature ratio differs between dawn and dusk sides and between high beta (around center of the plasma sheet) and low beta (around boundary of the plasma sheet) regions. No significant differences of the ion-to-electron temperature ratio are seen in both cases. The results may suggest that the mass dependence of plasma acceleration in the magnetotail reconnection is not related to the reconnection rate. We will discuss about what determines the occurrence distribution of the ion-to-electron temperature ratio.

太陽風変化時におけるホイッスラーモードコーラス波動の励起領域及び励起原因

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Response of electrons in near-Earth space to solar wind, and possible region where electromagnetic waves are excited

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The Earth is surrounded by energetic charged particles. The population of the energetic charged particles is called radiation belts. The growth and decay of the radiation belt are critical issues because these particles are hazardous to artificial satellites and human activities in space. To understand the growth and decay of the radiation belts, we need to understand two different processes. One is an adiabatic process in which adiabatic invariants of the particles are conserved. The other one is a non-adiabatic process in which the adiabatic invariants are violated. The non-adiabatic process is thought to occur when the particles interact with electromagnetic waves. The electromagnetic waves are excited when a certain condition of lower energy particles is set up by the adiabatic process. Toward the understanding of the radiation belts, we used the global magnetohydrodynamics (MHD) simulation (Tanaka, 2015; Ebihara and Tanaka, 2015) together with the advection simulation called Comprehensive Inner Magnetosphere-Ionosphere (CIMI) model (Fok et al., 2014). By MHD simulation, we calculated the response of the magnetosphere to the simulated solar wind change and by advection simulation, calculated the time evolution of the phase space of electrons. In MHD simulation, we imposed the following parameters to obtain steady state magnetosphere; the solar wind velocity of 400 km/s, the density of 5 /cc, the y component of interplanetary magnetic field (IMF) of 2.5 nT and the z component of IMF of 5 nT. To simulate an interplanetary (IP) shock, we changed the solar wind velocity to 980 km/s and the z component of IMF to -5 nT. In advection simulation, we gave electron temperature and density inferred from MHD simulation at the outer boundary. For an initial condition, we used AE8 model and kappa distribution. Using the velocity distribution function obtained by the advection simulation, we calculated the linear growth rate of the whistler-mode chorus waves as a response to IP shock and subsequent southward IMF. When the IP shock arrives at the dayside magnetosphere, the following occur subsequently. An increase in the hot electron density results in the increase in the number of electrons near resonance velocity (η). An increase in the magnetic field results in an increase in the perpendicular temperature of electrons, giving rise to an increase in the temperature anisotropy of resonant electrons (A^-). The linear growth rate of the whistler-mode chorus waves increased. At substorm expansion phase, the following occur subsequently. The enhanced electric field transports hot electrons deep inward, giving rise to an increase in the hot electron density, the η and A^- . The linear growth rate increases. We discuss the evolution of the region where the whistler-mode chorus waves can grow in response to the arrival of IP and the substorm.

地球の周囲には高エネルギー粒子が取り巻いており、高エネルギー粒子の集合体を放射線帯と呼ぶ。高エネルギー粒子の存在は人工衛星や、宇宙空間における人類の活動を脅かすものであり、従ってこの放射線帯の増減過程の理解は重要な課題である。この課題の達成に向けて、我々は2種類の加速過程を理解する必要がある。1つ目の加速過程は、断熱不変量が保存される「断熱過程」である。2つ目の加速過程は、断熱不変量が保存されない「非断熱過程」である。粒子が非断熱的に加速されるのは、粒子が電磁波と相互作用したときであると考えられており、電磁波は低エネルギー粒子が断熱過程によって、電磁電子ホールと、それに伴う共鳴電流が形成された際に励起される。

放射線帯の増減を理解するために、3次元グローバル電磁流体 (MHD) シミュレーション (Tanaka, 2015; Ebihara and Tanaka, 2015) と Comprehensive Inner Magnetosphere-Ionosphere (CIMI) model と呼ばれる移流シミュレーション (Fok et al., 2014) を組み合わせて使用した。MHD シミュレーションでは、模擬した太陽風の変化に対する地球磁気圏の応答を計算し、移流シミュレーションでは電子の位相空間の時間発展を計算した。MHD シミュレーションでは、境界条件として、太陽風の速度 400 km/s、密度 5 /cc を与え、惑星間空間磁場 (IMF) の y 成分 2.5 nT、z 成分 5 nT を与えた。また、太陽風の速度を 980 km/s、IMF の z 成分を -5 nT へと変化させることにより惑星間空間衝撃波を模擬した。移流シミュレーションでは、外側境界条件として MHD シミュレーションから得た温度、電場、磁場、密度、圧力の計算結果を与え、内側境界条件として粒子のフラックスを 0 とした。MHD シミュレーションから得た電場及び磁場は、シミュレーションの計算領域における背景場としても計算に使用した。電子フラックスの初期分布として AE8 モデルと kappa 分布とを組み合わせたものを用い、幅広いエネルギー、ピッチ角を持った電子を対象とした包括的なシミュレーションを行った。

上記の条件でシミュレーションを行った結果は以下のようであった。惑星間空間衝撃波が到来すると、(1) ホット電子密度及び磁場が上昇した。(2) 磁場の上昇によって電子の垂直方向運動量が上昇した。(3) ホット電子密度の上昇により、電磁波と共鳴する電子の密度 (η) が上昇した。それと同時期に、電子の垂直方向運動量の上昇によって共鳴する電子のピッチ角異方性 (A^-) が上昇した。(4) η 及び A^- が上昇した結果、サイクロトロン周波数で規格化した線形成長率が 0 から 0.001 へと上昇した。衝撃波到来から約 45 分後にサブストームが発生し、磁気圏真夜中から明け方にかけてにおいて、(1) 磁場及び電場が上昇した。(2) 電場の上昇によってホット電子密度が上昇した。(3) ホット電子密度の上昇によ

て、 η 及び A^- が上昇した。(4) η 及び A^- が上昇した結果、波の周波数で規格化した線形成長率は 0 から 0.002 程度にまで上昇した。

以上の結果から、惑星間空間衝撃波の到来や、サブストームの発生によって、それぞれ磁気圏昼側及び磁気圏真夜中から明け方にかけてホイッスラーモードコーラス波動が励起され、その結果電子の加速が行われ放射線帯の形成に繋がっている可能性があることがわかった。以後、ホイッスラーモードコーラス波動の非線形成長等も検討し、放射線帯の増減過程の理解を目指す。

昼側カusp・マントル沿磁力線電流系の定電流源

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Current generator of the dayside cusp/mantle field-aligned current system

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The important elements of a large-scale magnetosphere-ionosphere current system include the magnetospheric dynamo that maintains the voltage of the current system constantly and the current generator that produces the field-aligned currents (FACs) constantly. For the so-called region 1 and region 2 current systems, recent development of numerical simulation has almost clarified the physical processes of the above two elements. That is, the dynamo and the current generator are formed nearly at the same place, with the slow mode disturbance responsible for the dynamo and the Alfvén mode disturbance responsible for the FACs being coupled. In anticipation that the same mechanism is applicable to meso-scale FAC systems, this study focuses on the current generator of the dayside cusp/mantle FAC system. Here, the cusp/mantle currents indicate those associated with the cusp/mantle particle precipitation in the noon sector as identified by low-altitude satellites. This FAC system is known to be controlled by the dawn-dusk component (B_y) of the interplanetary magnetic field (IMF). Observations by low-altitude satellites indicate that when IMF B_y 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 B_y 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. Using the Reproduce Plasma Universe (REPPU) code developed by Tanaka [2015], we successfully reproduced the region 1/region 0 system in the noon sector. Based upon the results of this simulation, we discuss the current generator of the cusp/mantle FAC system in detail.

磁気圏-電離圏大規模電流系の重要構成要素に、定電圧を維持する磁気圏ダイナモと沿磁力線電流を生み出す定電流源がある。近年の数値シミュレーションの発展により、いわゆる region 1/region 2 電流系においては、両要素ともその物理過程がほぼ解明された。すなわち、ダイナモと定電流源はほぼ同じ場所に形成され、ダイナモを作る slow mode 擾乱と沿磁力線電流を作る Alfvén mode 擾乱が結合する。同様の機構がメソスケールの電流系にも適用できるのではという予想のもと、本研究は昼間側カusp・マントル沿磁力線電流系の定電流源に焦点を当てる。ここで言うカusp・マントル沿磁力線電流とは、低高度衛星で正午付近にカusp・マントルと同定される降下粒子領域に付随する沿磁力線電流である。この沿磁力線電流系は惑星間空間磁場の朝夕成分 (IMF B_y) に制御されることが知られている。低高度衛星の観測によると、IMF B_y 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 B_y 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uspに、高緯度側の region 0 がマントルに対応している。Tanaka [2015] が開発した Reproduce Plasma Universe (REPPU) コードを用いて、我々は真昼の region 1/region 0 を再現することに成功した。このシミュレーション結果に基づき、講演ではカusp・マントル沿磁力線電流系の定電流源について詳論する。

Characteristics of CME- and CIR-driven ion upflows in the polar ionosphere

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We investigated how velocity and flux of ionospheric ion upflows vary during magnetic storms driven by corotating interaction regions (CIRs) and coronal mass ejections (CMEs), using data from the European Incoherent Scatter (EISCAT) Tromsø UHF and Svalbard radars between 1996 and 2015. The characteristics of ion upflows were compared with ion and electron temperature variations measured with the EISCAT radars, and also joule heating rate, electric field, and field-aligned current (FAC) distribution derived from the Weimer model. Upward ion velocity increases in the nighttime at 66.2 degrees geomagnetic latitude just after the CIR- and CME-driven storms, corresponding to electron temperature enhancements due to soft particle precipitation and also ion temperature enhancements in the strong westward electric field region. The CME-driven storms have larger upward ion flux ($\sim 1.7 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$) than those under the CIR-driven storms ($\sim 0.3 \times 10^{13} \text{ m}^{-2}\text{s}^{-1}$). In the daytime, ion upflows are seen at 75.2 degrees geomagnetic latitude, with an upward flux of typically $10^{13} \text{ m}^{-2}\text{s}^{-1}$ for small CIR and CME storm cases. Substantial ion upflows last for a few days after the storm onsets under small CIR storms, whereas they last for only a day under small CME storms. Under both the cases, the substantial ion upflows are associated with an enhancement of the Region 1 FAC, eastward electric field and Joule heating rate. For large CME storms, substantial ion upflows are absent in the daytime probably due to equatorward expansion of the auroral oval.

編隊編成による磁気圏尾部リコネクションに伴うスローショックの直接観測

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In-situ observations of slow-mode shocks in the near-Earth magnetotail made by multiple spacecraft

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<http://www.eps.s.u-tokyo.ac.jp>

Magnetic reconnection which converts magnetic energy into thermal and kinetic energy of plasmas is an important physical mechanism of plasma heating and acceleration. Particularly in the Petschek-type reconnection, plasma acceleration and heating of the plasma in the slow-mode shocks formed at the separatrices must be taken into consideration. The structure of the slow-mode shocks in the distant-tail of the Earth's magnetosphere have been investigated by in-situ observations made by the GEOTAIL satellite (Saito et.al, 1998). It is observationally estimated that 3~20% of all ions entering the shocks are heated in the fore-shock region. It is, however, not fully understood what determines this ratio is how it is related with the ion-to-electron temperature ratio.

In this study, we utilized multi-spacecraft in-situ observations of the slow-mode shocks associated with magnetic reconnection in the near-Earth magnetotail. We used data obtained from FPI (Fast Plasma Instrument) and FGM (Fluxgate Magnetometer) on board the MMS satellite. We investigated events satisfying the one-dimensional Rankine-Hugoniot (RH) relations in which temperature anisotropy and heat flux are taken into account.

FPI (for burst-mode data) provides three-dimensional distribution function of ions (10eV ~30 keV) with a time resolution ~150ms and electrons (10eV ~30 keV) with the resolution of ~30ms, and FGM provides vector magnetic field data with ~8ms resolution. To determine the shock normal, we used the VSSz method (Vinas and Scudder (1986), Szabo (1994)). In the previous studies, shocks were assumed planer, but MMS multi-spacecraft observations will enable us to examine the shock shape.

An event of the slow-shock crossing was observed by MMS1 at X.GSM ~22 RE on 17 June 2017. Errors in the upstream and downstream of the 6 conserved quantities in the RH relations were within 30%. The upstream and downstream flow speeds satisfied the slow-mode shock conditions. We found that cold ions were heated in the fore-shock region. Similar characteristics are seen in other events. We will examine the detail structures in the fore-shock region and the transition layer and variations of velocity distribution functions to discuss heating and acceleration processes around the slow-mode shocks.

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磁気リコネクションは磁場エネルギーをプラズマの熱エネルギー・運動エネルギーに変換する重要な物理機構である。特に Petschek リコネクションにおいてはその散逸領域に加えて、境界に形成されるスローショックにおけるプラズマの加速・加熱の影響を加味しなければならない。磁気圏尾部遠方におけるスローショックの構造については、GEOTAIL 衛星等を用いた直接観測によって明らかにされてきた (Saito et.al, 1998)。加速・加熱における重要な構造として、スローショック前面において加熱されるイオンがあげられる。観測的にはショックに流入する全イオンに対し 3~20% 存在することが分かっているが、どのようにしてその割合が決定されるのか、また電子とイオンの温度比の関係については明らかになっていない。

本研究では、磁気リコネクションに伴って生成する地球近傍における磁気圏尾部のスローショックについて、複数編隊衛星による直接観測を用いた。具体的には、MMS 衛星の粒子観測器 FPI(Fast Plasma Instrument)、磁場観測機 FGM(Fluxgate Magnetometer) から得られたデータを基に、ロープ・プラズマシート境界を観測したイベントのうち、温度異方性・ヒートフラックスを考慮した Rankine-Hugoniot(RH) 関係式を満たすイベントを解析した。FPI の時間分解能はイオンで ~150ms、電子で ~30ms(burst-mode の場合)、FGM は ~8ms であり、従来の観測機器と比べて高時間分解能のデータを得ることができる。また衝撃波の Shock normal を決定するにあたり、Coplanarity よりも高精度な VSSz 法 (Vinas and Scudder(1986), Szabo(1995)) を用いた。またこれまでの研究では衝撃波は平面衝撃波を仮定してきたが、MMS 衛星の 4 機編隊飛行により衝撃波の形状を含めた分析をすることができると考えている。

イベント例として、6/17 に観測されたものを挙げる。MMS 1号機 (GSM-x ~22Re) により観測され、RH 関係式における 6 つの保存量の上流・下流の誤差は 30% 以内であった。上流・下流のフロー速度はスローショックの要件を満たしている。このイベントの解析の結果、先述したようなスローショック前面における冷たいイオンの加熱が見られた。これは現

在解析を進めている他の2イベントにも共通している。また、このような衝撃波前面における加熱に関わる構造に加え、遷移層における詳細な構造とプラズマ速度分布関数の変化を解析し、衝撃波におけるプラズマ加熱を議論する。

cusp-magnetosheathにおけるショックの消長と substorm の関係 (2)

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Variations of the dayside magnetosheath and the cusp and their relations to the substorm sequence (II)

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In the last JpGU meeting, we explained the physical mechanisms of formation of a transient shock in the magnetosheath during the growth phase of a substorm, and its disappearance after the growth phase by using a global MHD simulation and its relation to the substorm sequence. In that talk, we clearly explained formation of the shock in the magnetosheath, but it was not so clear to explain the disappearance mechanism. This mechanism seems to be related to plasma depression in the near-Earth plasma sheet in the substorm expansion phase. We will investigate this mechanism based on the simulated plasma behavior. In addition, we notice that the plasma depressions in the near plasma sheet appear so frequently. This will be also touched in the talk. In the talk, we will summarize the formation mechanism of the shock, and present new findings about the plasma disturbances which cause disappearance of the shock.

昼側磁気圏境界面付近における運動論的アルフベン波によるプラズマ輸送過程の直接観測

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Direct measurement of plasma transport process via kinetic Alfvén waves near the dayside magnetopause

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Plasma transport via kinetic Alfvén waves (KAWs) has been a candidate process to drive transport of the solar wind plasma into the magnetosphere. In order to verify the transport process from in-situ plasma measurements, it is necessary for plasma measurement to have a time resolution of about 1 sec or less, which is a typical wave period of KAWs near the magnetopause. This time resolution was not achieved by conventional missions, but has recently been achieved by the NASA's Magnetospheric Multiscale (MMS) mission (150 msec for ions and 30 msec for electrons) launched in 2015. In this study, we investigate the plasma transport process via KAWs by analyzing the plasma data obtained by the MMS spacecraft as follows: we compare the velocity moment for particles that satisfy the condition for the Landau resonance with KAWs with the velocity of resonant particles predicted by a linear theory (Izutsu et al., 2012). From the above analysis, we quantitatively assess the particle transport process induced by KAWs.

太陽風起源のプラズマ粒子が磁気圏内へ輸送される過程の一つとして、運動論的アルフベン波 (KAWs) による輸送過程が提案されている。この粒子輸送過程をプラズマ観測から解明するためには、磁気圏境界面付近の KAWs の典型的な周期である 1 秒程度以下の時間分解能でのプラズマ観測が必要であるが、従来の衛星観測では達成されていなかった。この時間分解能は、2015 年に NASA によって打ち上げられた Magnetospheric Multiscale (MMS) ミッションによって達成されている (イオン: 150 ミリ秒、電子: 30 ミリ秒の時間分解能)。このため、本研究では MMS 衛星によるプラズマ観測データを用いて、運動論的アルフベン波 (KAWs) によるプラズマ輸送過程を直接観測することを目的とし、以下の解析を行う。粒子輸送が効率的に起こると考えられる、KAWs とのランダウ共鳴条件を満たすエネルギー帯の粒子に対する速度モーメントと、線形理論 (Izutsu et al., 2012) によって予想される共鳴粒子の運動速度を比較する。上記の解析によって KAWs による粒子輸送過程を定量的に解明することを目指す。

GEOTAIL 衛星搭載低周波電界アンテナインピーダンスの解析

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Analysis of Low-Frequency Electric Field Antenna Impedance Aboard GEOTAIL

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The GEOTAIL spacecraft has two types of wire antennas to observe low-frequency electric fields of space plasma waves. For obtaining the accurate electric fields observed with such antennas (i.e., for accurate calibration of electric-field receivers), it is important to know the effective length and impedance of each antenna in magnetospheric plasmas. So far we have analyzed the characteristics of the effective lengths of the wire antennas. On the other hand, the antenna impedance varies with ambient plasma parameters. GEOTAIL can directly measure the antenna impedances in-situ. Since the exact calibration of electric fields has been difficult, 'typical' values of antenna impedance measured in several regions in the magnetosphere were used for calibration. It is necessary to know the accurate impedance at each location of GEOTAIL, for accurate analysis of propagation characteristics (polarization, Poynting vector, etc.) of plasma waves.

In this study, we estimate accurate antenna impedance values by using chorus emissions in the magnetosphere observed by the wave form capture (WFC) of the plasma wave instrument (PWI). For the whistler mode waves like chorus emissions we can theoretically evaluate their propagation characteristics, to obtain the theoretically expected electric field components only from the wave magnetic field observations by search coil magnetometers. Then we derive the theoretical values of refractive index, and compare them with the observed electric field components, to estimate the detailed variation of the antenna impedance. In the presentation, we will quantitatively discuss the impedance characteristics of the electric antenna onboard GEOTAIL in the Earth's magnetosphere.

GEOTAIL 衛星では磁気圏プラズマ中の電磁波動観測において低周波電界センサとしてワイヤアンテナとプローブアンテナが用いられている。これらのアンテナで観測された電界はアンテナインピーダンスや実効長、また測定回路の影響を受けるため、回路の出力電圧から電界の値への較正が必要になる。正確な較正にはプラズマ中でのアンテナ実効長及びアンテナインピーダンスの値が必要である。これまで我々はアンテナ実効長の解析を行い、その特性を明らかにしてきた。一方アンテナインピーダンスは衛星周辺のプラズマパラメータにより影響を受け変化することが分かっている。GEOTAIL 衛星ではアンテナインピーダンスを直接計測することができ、それを電界の較正に用いている。しかし磁気圏内のいくつかの領域で計測された値を、その領域での代表値として用いているため、個々のデータにおいては電界が正確に較正されていない可能性がある。プラズマ波動の伝搬特性（偏波、ポインティングベクトル等）を正確に調べるためには、個々のデータに対して正確なアンテナインピーダンスの値を知る必要がある。

本研究ではコーラスエミッションのデータを用いて、正確な電界アンテナインピーダンスの値を求めることを目標としている。コーラスエミッションのようなホイストモード波はその伝搬特性（屈折率）を理論的に評価できるため、磁界センサ（サーチコイル）による波動の磁界成分の観測データのみから電界成分の理論値を求めることができる。ここでは GEOTAIL 衛星搭載のプラズマ波動観測装置 (Plasma Wave Instrument: PWI) の波形捕捉受信器 (Wave Form Capture: WFC) で測定したコーラスエミッションの電磁界波形データを用いて、アンテナインピーダンスの推定を行う。電界成分の理論値及び電界センサによる観測値から計算した屈折率を比較することで、アンテナインピーダンスの値を推定する。発表では、コーラスエミッションが観測される磁気圏領域における屈折率の変化に基づき、アンテナインピーダンスの特性変化を定量的に議論する。

New observation of MF/HF radio emissions in the northern Scandinavia

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We have launched a new research project of ground-based observation of MF/HF radio emissions. As a first step, we install a new dedicated instrumentation at the KAIRA (Kilpisjarvi Atmospheric Imaging Receiver Array) site in Kilpisjarvi, Finland (Latitude: 60.07 N, Longitude: 20.76 E) in the summer of 2018. It is a passive receiving system designed to realize a high-resolution spectral, interferometric and polarization measurements using 4 loop antennas and a software-defined radio (SDR) receiver, USRPTM (Universal Software Radio Peripheral). This SDR receiver can implement high-speed, flexible digital signal processing of RF signals and obtain high-resolution spectra pauselessly throughout the night in a wide frequency range up to 6 MHz. One of the main research subjects of this project is radio emission spontaneously emitted from aurora. There are long-known three types of MF/HF auroral radio emissions identified at ground level: auroral hiss, medium frequency burst (MFB), and auroral roar. In addition, recent studies have resulted in ground-level detection of auroral kilometric radiation and discovery of a natural radio emission between f_{ce} and $2f_{ce}$. Investigation into the generation of these emissions not only offers a tool of great promise for remote sensing of ionospheric plasma processes and parameters but also gives the foundation for understanding various radiation mechanisms that occur in planetary magnetospheres and plasma in space. In combination with a similar passive receiver system previously installed in Svalbard and Iceland and future EISCAT_3D experiments, observation with this new instrumentation will provide a first-time opportunity to reveal spatiotemporal variations of macro and fine structures of MF/HF auroral radio emissions associated with substorm evolution. In this presentation, we show detailed specification of this instrumentation and some initial results.

FPGA を用いたスペクトルマトリクス演算モジュールの開発

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Development of an FPGA module for spectral matrix

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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 the 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 developed an FPGA module for the data production of spectral matrix that is useful for direction finding of the plasma waves and verified its function by simulation. According to the verification result, it was confirmed that electromagnetic field waveform data can be processed in real time with this module. As a next step, it is necessary to evaluate data qualities using real observation data, because the calculation with the FPGA module is done in fixed point operations. In the present study, we present the evaluation results of the spectral matrix generated by the developed FPGA module using the observation data from the PWE (Plasma wave experiments) on board the Arase satellite.

In the presentation, we report the configuration of the design and the performance of the spectral matrix module, and finally show the evaluation results of the generated spectral matrices when we feed the waveform data obtained by the PWE on board the Arase satellite.

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先行研究において、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 モジュールを開発し、シミュレーションによる動作検証を行った。検証結果により、電磁場波形データをリアルタイムに処理可能であることが確認された。しかし、FPGA モジュールでの計算は固定小数点演算で行われるため、実観測データを使用して処理結果を評価する必要がある。そこで、本研究では、ジオスペース探査「あらせ」衛星に搭載されている PWE(Plasma wave experiment) の観測データを用いて、開発した FPGA モジュールで生成したスペクトルマトリクスの評価結果を示す。

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を報告し、最後に、あらせ衛星に搭載された PWE の観測データを用いたときに生成されるスペクトルマトリクスの評価結果を示す。

地球磁気圏内における ULF 波動に対する多点衛星観測データを用いた波動ベクトル解析

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Wave vector analysis using multi-spacecraft observation on ULF waves in the magnetosphere

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Wave vector analysis techniques utilizing multi-spacecraft observations, such as the four spacecraft of the Cluster mission, 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 for the first time. It is important to measure the wave vectors directly by in-situ observations for estimating the energy transportations and diffusion coefficients. We applied the wave vector analysis techniques to ULF waves in the terrestrial magnetosphere, including the electromagnetic ion cyclotron waves and their rising tone emissions. The estimated frequency-wave vector distributions agree with those calculated by the linear theory, but tend to disagree when the spacecraft are close to the wave sources.

Simulation of nonlinear damping for obliquely propagating whistler-mode wave

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We perform two-dimensional electromagnetic particle simulation to study fundamental characteristics of whistler mode wave-particle interaction involved in chorus emissions propagating oblique to the background magnetic field. We assume periodic (x , y) system with the parabolic magnetic field taken in the x -direction. With the electrostatic components parallel to the magnetic field, which have been neglected in the previous simulation studies on chorus emissions, the distribution function in position can have a great influence on the simulation results. Assuming energetic electrons with anisotropic subtracted bi-Maxwellian velocity distribution function at the equator, we first put particles under harmonic bounce motion under a parabolic magnetic field. We next follow the motions of the particles adiabatically without any waves to obtain an equilibrium state as the initial distribution for the particle simulation. It is necessary to put many super-particles in a grid cell to suppress the thermal fluctuation. With 8,192 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 perpendicular to static background magnetic field and oscillate the antenna current with phase delay, which satisfy matching condition for wave phase at boundaries. Oblique propagating whistler-mode wave with variable frequency is excited from phased array antenna. 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.

機械学習によるフラッシュオーロラの自動検出

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Automatic detection of flash aurora by a deep learning technique

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High energy charged particles move along geomagnetic field lines and precipitate into the Earth's atmosphere, then auroras are shown on the ground. In other words, the aurora is a clue to know the behavior of high energy charged particles in the magnetosphere from the ground. In order to prevent damage to commercial satellites and astronauts by geomagnetic storms, we have studied automatic detection of aurora by deep learning techniques. In this study, we focus on a specific aurora which we call flash aurora.

The flash aurora shows a patchy structure with a small spatial scale (less than several tens of km) and a sudden emission less than one second. It can be different with pulsating auroras showing a quasi-periodic (several to tens of seconds) variation of the brightness. It is difficult to detect a lot of events by visually looking because the shape of flash aurora changes with the emission time of several tens to hundreds of milliseconds, which is difficult to capture with human eyes. We conducted automatic detection of flash aurora appearance using a deep learning technique. The observed auroral data used high frame rate all-sky EMCCD images (100 Hz sampling and 256 times 256 pixels) observed at Gakona (Alaska). We used a convolution neural network (CNN), which is known that CNN has particularly excellent for image recognition. For learning data, we use visually classified a Keogram image (2400 times 720 pixels, 1-minute period) that obtained by segmenting the north-south cross section of all-sky EMCCD data in a time-series order and dividing it into square blocks (30 times 30 pixels, 750-ms period). These are classified into 4 types such as pulsating aurora, flash aurora, noise, no aurora and noise. When we actually detect the flash aurora by using the CNN, the area that pulsating aurora showing luminosity variations with several seconds is detected as pulsating aurora, and the area that aurora emitting for less than one second is detected as flash aurora. Therefore, we found that detection results applying to the Keogram images were appropriately classified. When we analyzed the test data using the CNN created in this time, its accuracy was 95.25%.

In this presentation, we will report our automatic detection method of flash aurora and its accuracy in detail.

オーロラは高エネルギーの荷電粒子が磁力線に沿って移動し、地球上層大気と衝突することで発光する現象である。つまり、高エネルギー荷電粒子の振る舞いを表すオーロラは宇宙空間の様子を地上から知る手掛かりとなる。このことから、磁気嵐による商用衛星や宇宙飛行士への被害を防ぐために、本研究ではオーロラ現象を機械学習によって自動検出することを試みる。今回は、特にフラッシュオーロラと呼んでいるオーロラを検出対象とする。

フラッシュオーロラとは、比較的小規模な空間スケール(数十 km 程度)のパッチ形状をもつオーロラである。数秒から数十秒の明滅周期をもつ脈動オーロラとは異なり、前後の時間で他のオーロラ現象が現れずに単独で突発的に発光する。また、人間の目では捉えることが困難な数十~数百 msec の発光時間で、パッチ形状が変化するため、大量のイベント検出を目視で行う事が難しいという特徴もある。そこで、我々はフラッシュオーロラのイベント検出を単純化すべく、機械学習を用いてフラッシュオーロラ出現部の自動検出を行った。観測データは、ガコナ(アメリカ・アラスカ州)に設置された全天 EMCCD データ(サンプリング 100 Hz、解像度 256*256 ピクセル)を用いた。また、本研究で用いた機械学習の手法は、画像認識に特に優れている畳み込みニューラルネットワーク(CNN)である。学習データは、全天 EMCCD データの南北断面を切り出して時系列に並べた Keogram 画像(解像度 2400*720 ピクセル、時間幅 1 分間)を正方形のブロック(解像度 30*30 ピクセル、時間幅 0.75 秒間)に分割し、目視で分類したものを学習データとして使用した。分類は、脈動オーロラ、フラッシュオーロラ、雑音、オーロラ・雑音共になしの 4 種類とした。実際に CNN を用いてフラッシュオーロラを検出すると、脈動オーロラが数秒間発光している所は脈動オーロラ、1 秒以下で発光している所ではフラッシュオーロラと検出され、Keogram 画像と検出結果が適切に対応していることが分かった。今回作成した学習ネットワークを使用して、テストデータを分類したところ、その精度は 95.25%であった。

本発表では、我々が開発しているフラッシュオーロラの自動検出法とその精度について詳細に報告する予定である。

脈動オーロラロケット Rocsat-XN と LAMP の開発ならびに将来超高大気観測衛星 計画 FACTORS

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Rocket experiments Rocsat-XN and LAMP, and a future satellite mission FACTORS for understanding aurora and upper atmosphere

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We report two rocket experiments Rocsat-XN and LAMP for understanding high-energy electron precipitation associated with pulsating aurora, and also present a future satellite mission FACTORS which aim to understand the coupling processes in the terrestrial magnetosphere/ionosphere/thermosphere. In-situ and remote-sensing observations are essential to understand complicated auroral phenomena. Recent advances of measurement techniques enable us to obtain precise auroral and plasma parameters with high-time and spatial resolutions even using a commercial-based instrument, and it is worth to propose rocket/space experiments based on unique idea.

We are now carrying out two sounding rocket projects, Rocsat-XN/PARM and LAMP/PARM2. The Rocsat-XN rocket is scheduled to be launched from Andoya, Norway in January 2019. In this rocket we carry out simultaneous auroral imaging and medium- and high-energy electrons to understand the generation and loss process of high-energy electrons associated with pulsating aurora. The auroral imaging camera (AIC) will measure the optical thickness and imaging of pulsating aurora at magnetic footprint of rocket. AIC observes mainly N2 1PG aurora with the RG-665 filter, Watec 910HX CCD and wide FOV lens (FOV of 96 deg x 75 deg). So far, we completed all of the tests in Japan, such as intensity calibration, electrical interface tests, environmental (vacuum, vibration and thermal) tests and confirmed their sufficient performances. We have shipped the instruments to NASA Wallops, and are now carrying out interface tests there. In addition, we started another rocket experiments LAMP under collaboration with University of New Hampshire, and two auroral imagers will be installed to measure different auroral emissions. LAMP will be launched in winter of 2019 from the Poker Flat research range.

Further, we started discussion on a future mission called FACTORS (Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by Outer Space Research System) as a community exploration mission in Japanese space research after the success of the ERG mission. This will measure the precise structure of auroral acceleration region, particle transportation between ionosphere and magnetosphere, and thermosphere-ionosphere coupling using two formation flight satellites. Possibility of third satellite by Sweden is now in under discussion. We mainly concern on optical and ultra-violet remote sensing of aurora and airglow for this mission. A visible imager will measure small-scale auroral structures at a wavelength of auroral prompt emission line with high-time (~0.1s) and high-spatial (~1km) resolutions using EMCCD. The FOV of 8 x 8 deg covers an area of 400 x 400 km viewed from altitudes of 3000 km. The far-ultraviolet (FUV) imager adopts a wide (~50 x 50 deg.) FOV objective mirror system which covers ~3000 x 3000 km area viewed from 3000 km altitude. FUV imager adopts a filter wheel to change the wavelength between O 135.6 nm and the N2 LBH band at 140-160 nm to estimate O/N2 ratio. Wide-field N2 image enable us to examine large-scale auroral dynamics like westward-travelling surge during substorm, and O/N2 images provide us to understand the global thermospheric activity.

観測パッケージ PARM-HEP による脈動オーロラ現象に伴う高エネルギー降り込み電子の観測

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PARM-HEP Observation of Precipitating High Energy Electrons over Pulsating Aurora

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The Pulsating Aurora (PsA) is one of the auroral phenomena whose emission intensities are modulated quasiperiodically in a few to tens of seconds. This quasiperiodicity is accounted for periodic precipitation of a few to tens of keV electrons which is thought to be generated by pitch angle scatterings due to whistler mode chorus waves in the magnetosphere. The PsA also has fine internal modulations, which are thought to be related to the repetitive appearance of rising tone elements of the lower band chorus waves in a short interval (a few Hz). On the other hand, microburst precipitations of relativistic electrons are often observed by low-altitude satellites. Recent numerical simulations successfully reproduce these microburst precipitations with a few Hz modulations by taking into account the pitch angle scattering with the whistler chorus elements at high latitudes. However, relationship between the PsA internal modulations and the microbursts is still unknown.

We have developed a high-energy electron detector (HEP) in order to understand the relationship between PsA and the electron microburst precipitations. HEP is designed to measure electrons with energies ranging from 300 keV to 2 MeV with high-time resolution. Minimum energy resolution of HEP is less than 5 %, and 1 event processing time is less than 5 μ s based on the laboratory experiments using 1 MeV electron beam. HEP is a part of PARM (Pulsating AuroRa and Microburst) package to be onboard the RockSat-XN sounding rocket which will be launched from Andoya, Norway in winter season of early 2019. PARM consists of four instruments, High Energy Particle detector: HEP, which is above-mentioned, Medium Energy particle Detector: MED, Auroral Imaging Camera: AIC, and ASIC FluxGate magnetometer: AFG. Energy range of electron measurement provided by PARM is extended by MED down to 20 keV.

In this presentation, we will show the outline and test results of HEP as well as the current status of the preparation for the launch of RockSat-XN.

脈動オーロラは数秒~数十秒の準周期性をもって明滅するような、オーロラ現象の一つである。この準周期性は地球磁気圏でのホイッスラーモードコーラス波によるピッチ角散乱によって周期的に降り込んだ、数~数十 keV の電子によるものであるとされる。また、脈動オーロラには微細な内部変調が存在しており、コーラス波を構成する要素の数 Hz 間隔の繰り返しに関連していると考えられている。一方脈動オーロラが観測されている時間帯には、相対論的電子のマイクロバースト降り込みが低高度の衛星により観測されている。最近のシミュレーションではこうした数 Hz でのマイクロバースト降り込みを、高高度でのコーラス波要素によるピッチ角散乱によって再現することに成功している。しかし、依然として脈動オーロラの内部変調とマイクロバーストの関係性は解明されていない。

我々は脈動オーロラと電子マイクロバースト降下の関係性を調べるため、高エネルギー電子観測器 (HEP) を開発した。HEP は 300keV~2MeV の高エネルギー電子を高時間分解能で観測することを目的として設計されており、試験の結果 1MeV 電子を、最小エネルギー分解能 5 %以下、1 イベント処理時間 5 μ s 以下で計測することが可能である。

HEP は、脈動オーロラのメカニズム解明を目的とした PARM (Pulsating AuroRa and Microbursts) 観測器パッケージの一部として、2019 年初頭にノルウェー・アンドーヤから打ち上げられる観測ロケット RockSat-XN に搭載される予定である。PARM は前述した高エネルギー電子観測装置: HEP、中エネルギー電子観測装置: MED、光学カメラ: AIC、フラックスゲート磁力計: AFG の 4 つの観測機器から構成される。PARM によって観測される電子のエネルギー幅は、20keV (MED) から 2MeV (HEP) である。

本発表では、HEP の概要と試験結果、さらに現在の打ち上げ準備状況について述べる。

PARM計画：脈動オーロラ観測ロケット Rocksat-XN 搭載オーロラカメラの開発

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PARM project: Development of an auroral camera for the pulsating auroral experiment PARM on the Rocksat-XN rocket

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We are developing an Aurora Imaging Camera (AIC) for the pulsating auroral experiment Pulsating AuRora and Microburst (PARM) on the Rocksat-XN rocket which is scheduled to be launched in January 2019 at Andoya space center to clarify the relationship between high-energy electron precipitation and pulsating aurora (PsA). In this presentation, we mainly focus on the development and current status of AIC, and also report the mission purpose and plan.

It is suggested that high energy electrons (>100 keV) precipitate down to about 70 km altitude during the PsA [Miyoshi et al., 2015]. However, there is no simultaneous observation between such high-energy electrons and PsA. On the other hand, Jones et al. [2009] estimated the thickness of the PsA to be 15-25km by ground radar observations. However, there are no direct measurement of the thickness of PsA by rocket.

PARM consists of an intermediate energy (20 - 100 keV) electron detector MED, high energy (several hundred keV - 2 MeV) electron detector HEP, fluxgate magnetometer AFG, and auroral camera AIC. AIC will observe the thickness of the emission layer of PsA directly and captures horizontal distribution of PsA fluctuation at the magnetic footprint.

As a development of AIC, we conducted sensitivity calibration experiment, performance evaluation, assembly, environmental test. AIC consists of detector unit AIC-S and power/data processing electric unit AIC-E. AIC-S consists of a CCD camera (Watec 910 HX), wide-angle lens (F value:1.6, focal length:3.5 mm) with a field of view in the vertical direction of 96.4 degrees and in the horizontal direction of 74.0 degrees, and an optical filter (RG665) that transmits light with a wavelength of >665 nm. Although the number of CCD pixels is 756×482 , 24×30 pixel binning is performed for data compression and sensitivity improvement, and the spatial resolution of one frame is 31×16 bin. The imaging interval of AIC data is 100 ms and the exposure time is 67 ms.

We carried out the development of AIC, such as sensitivity calibration using the integrating sphere of the National Institute of Polar Research on March 12, 2018, focus alignment, and environmental tests. To estimate sensitivity of PsA emission, we must take into account the spectra of PsA in the wavelength range of RG665 filter since the integrating sphere emission is continuum. We used typical PsA spectra obtained at 3:00-4:00UT on March 3, 2017 at Norway Tromsø. However, the spectral range was limited in the 480-880, while the CCD on AIC has a sensitivity up to 1025 nm. Thus, we infer the PsA spectra in the range of 880-1025 nm by Hunten [1958]. As a result, $S/N > 5$ and $S/N > 18$ are expected to obtain when PsA intensity is ~ 10 kR, and 50 kR the exposure time of 67ms. The saturation level of the AIC is estimated to be >100 kR, which is sufficient to observe the auroral intensity integrated along the limb direction.

The AIC focus adjustment was conducted on 12th to 13th July 2018. Taking image data for the target far from 85, we adjusted the distance between lens and CCD detector using precise shim rings. Environment tests (vacuum, vibration test, and temperature) of AIC were conducted from 18th to 20th July 2018, and we confirmed sufficient performances of AIC. In the vibration test, random vibration of 10 Grms, sine wave vibration at maximum of 7G were put in the Z axis direction. For the X and Y axes, random vibration of 7.6 Grms was conducted respectively. In the temperature, putting AIC in the thermostat we changed the temperature from 0 to 50 degree at atmospheric pressure level, and confirmed the performance of AIC.

Rocksat-XN ロケット実験は、高エネルギー降下電子と脈動オーロラ (PsA) の関係を解明することを目的としている。今回我々は、これに搭載されるオーロラ観測カメラ (AIC) の開発成果を報告する。

PsA 発光時、高エネルギー電子 (>100 keV) が降り込み、中間圏高度 70km 付近まで電離する可能性が地上レーダー観測により示唆されている [Miyoshi et al., 2015]。しかし、PsA 発生時の 100keV 以上の降下電子をその場観測した事例報告されていない。また、降下電子のエネルギー分布によって決定される PsA の発光層の厚さについて、S.L. Jones et al., [2009] は地上レーダー観測からその厚さを 15km-25km と見積もったが、PsA 発光層の厚さをロケット観測で見積もった例は未だにない。

米国とノルウェーが主催し、2019年1月に Andoya Space Center から打ち上げられる Rocksat-XN ロケット実験には、日本から Pulsating AuroRa and Microburst (PARM) という観測機器群が搭載され、地上観測と共同で PsA 現象を観測する。PARM は、中間エネルギー (20 - 100keV) 電子計測器 MED、高エネルギー (数百 keV - 2MeV) 電子計測器 HEP、フラックスゲート磁力計 AFG、オーロラカメラ AIC から構成される。AIC はこの観測実験において、PsA の発光を観測する事で、発光層の厚さの直接観測ならびに上空から磁力線方向の PsA 変動を捉える。

我々は AIC の開発として、感度校正実験、性能評価、組み上げ、環境試験を行った。AIC は検出器ユニット AIC-S と

電源・データ処理エレキユニット AIC-E から構成される。AIC-S は、波長 665nm 以上の光を透過させる光学フィルター (RG665)、垂直方向 96.4 度、水平方向 74.0 度の広角レンズ (F 値 1.6、焦点距離 3.5mm)、CCD カメラ (Watec 910HX) からなる。CCD 画素数は 756 x 482 だが、データ圧縮と感度向上のため 24 x 30pixel ビニングを行い、1 画面 31x16bin の空間分解能となる。AIC データの撮像インターバル 100ms であり、露光時間は 67ms ある。

我々は、2018 年 3 月 12 日に国立極地研究所の積分球を用いて校正実験を行った。この積分球は連続光であるため、RG665 フィルター透過帯における PsA スペクトルを用いて、PsA 観測時の感度を見積もる必要がある。PsA スペクトルは、ノルウェー・トロムソにおける 2017 年 3 月 3 日 3:00-4:00UT に観測された典型的な PsA 発生時のものを用いた。ただし、このスペクトル観測は 480-880nm の範囲のみである一方で、AIC の CCD 感度は 1025nm まで感度を有するため、880-1025nm の範囲は Hunten[1958] の赤外オーロラスペクトルを用いて推定した。積分球による校正結果と PsA スペクトルデータを組み合わせ、AIC 観測波長範囲の PsA 強度の明滅が >10kR で変動している際、露光時間 67ms で AIC は視野中心において S/N>5、同様に 50kR の PsA では S/N>18 という十分な感度を達成することがわかった。また、この設定で AIC の飽和レベルは 100kR 以上であり、リム方向を見ても飽和することは無いと考えられる。

AIC のフォーカス調整は 2018 年 7 月 12 日から 13 日にかけて行われた。敷地内にある 85m より遠い距離の対象物の構造を撮像し、フランジバックの距離を精密シムリングによって調整した。

AIC の環境試験 (真空試験、振動試験、温度試験) は 2018 年 7 月 18 日から 20 日にかけて行われ、いずれの AIC は十分な性能を満たすことを確認した。振動試験では、RockSat-XN の要求レベルすなわち Z 軸方向にランダム加振 10Grms、正弦波加振最大 7G、X 軸ならびに Y 軸ランダム加振 7.6Grms をあたえた。振動試験における AIC 性能評価は、加震前後で画像を取得し、その変化がないことを確認することで実施した。温度試験では、大気圧で 0℃ から 50℃ まで変化させながら AIC のダークデータならびに光を入射させてデータを取得し、AIC の動作確認を行った。