GEMSIS 環電流-放射線帯モデル結合に基づく Pc5 波動による相対論的電子の動径方向輸送の特性に関する研究

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Study on radial transport of relativistic electrons by Pc5 waves in the inner magnetosphere based on the GEMSIS-RC and RB models

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http://st4a.stelab.nagoya-u.ac.jp/gemsis/

Acceleration mechanisms to cause drastic variation of the Earth's outer radiation belt are one of outstanding problems of the magnetospheric researches. While the radial diffusion of the electrons driven by ULF waves in Pc5 frequency range has been considered as one of the candidate mechanisms, it is pointed out that the radial transport of relativistic electrons by ULF waves is not necessarily reach the radial diffusion limit and collective motion of the outer belt electrons can exhibit large deviations from the radial diffusion [Ukhorskiy et al., JATSP, 2008]. If the radial transport deviate from the diffusion limit, one cannot deny the contribution of Pc5 radial transport simply by the radial profile of the electron phase space density. Thus it is important to understand the form of radial transport of electrons under realistic ULF distribution in the inner magnetosphere. We have developed a physics-based model for the global dynamics of the ring current (GEMSIS-RC model). The GEMSIS-RC model is a self-consistent numerical simulation code solving the five-dimensional collisionless drift-kinetic equation for the ring-current ions in the inner-magnetosphere coupled with Maxwell equations [Amano et al., JGR, 2011].

We applied the GEMSIS-RC model for simulation of global distribution of ULF Pc5 waves. Comparison between runs with/without ring current ions show that the existence of hot ring current ions can deform the original sinusoidal waveforms. The deformation causes the energy cascade to higher frequency range (Pc4 and Pc3 ranges). The cascade is more pronounced in the high beta case. It is also shown that the existence of plasmapause strengthens ULFs outside the plasmapause and widens the MLT region where the E_r (toroidal) component is excited from initially-given E_phi (poloidal) component. In order to investigate the characteristics of radial transport of relativistic electrons, we then use the global magnetic and electric fields variation obtained by the GEMNIS-RC model as input field models for the test particle simulations of radiation belt electrons (GEMSIS-RB) [Saito et al., JGR, 2010]. The combination of GEMSIS-RC and RB models reproduced rapid radial transport by the drift resonance for simple monochromatic wave inputs as theoretically expected. On one hand, collective motion of the relativistic electrons shows deviations from the radial diffusion limit for large amplitude case due to finite system size. We will discuss a possible threshold of the Pc5 amplitude to cause the deviations.

Correlation between relativstic electron flux and EMIC rising-tone emissions observed by the Van Allen Probes

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Spacecraft observations and simulations have revealed generation of coherent electromagnetic ion cyclotron (EMIC) rising-tone emissions in the inner magnetosphere [1,2]. The EMIC rising-tone emissions have recently received much attention because of the possibility of their strong nonlinear interaction with relativistic electrons [3]. We present the observation of EMIC rising-tone emissions from the Van Allen Probes. We have found that a number of EMIC rising-tone emissions were detected by the EMFISIS Waves instrument on the Van Allen Probes, and that some EMIC rising-tone emissions accompanied by a variation of the electron flux. On 23 February 2014, EMFISIS detected strong EMIC rising-tone emissions excited repeatedly in the dayside magnetosphere(MLT ˜13 and L˜6). In this period, the Magnetic Electron Ion Spectrometer (MagEIS) shows that relativistic electron fluxes fluctuate at the same time with the rising-tone emissions. We can also find that fluxes of electrons with the energy greater than about 0.4 MeV decrease and the minimum energy changes according to the maximum frequency of each EMIC rising-tone emission.

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プルーム領域におけるEMIC波動の増幅と関連するPc3-4波動

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Amplification of EMIC waves in the plume region and related Pc3-4 waves

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The electromagnetic ion cyclotron (EMIC) wave is one of the key phenomena for the dynamics of high-energy electrons in the radiation belt, since EMIC waves can scatter particles and precipitate them into the ionosphere from the inner magnetosphere. The scattering by EMIC waves could be responsible for the slot region formation in the radiation belt. In order to evaluate the impact of EMIC waves to the radiation dynamics, it is important to understand that when and where significantly strong EMIC waves are excited and interact with particles.

The EMFSIS instruments of Van Allen Probes observed proton-band EMIC waves with the frequencies 2-6Hz at r~3Re in the GSM coordinates at 1110-1140UT on 29 June 2013. The wave event occurred during the recovery phase of the magnetic storm started on 27 June. This event displays large enhancements of wave amplitudes up to ~10nT at 1123 and 1130UT. At the time of the enhancements, the satellite crossed a plume region identified by the upper hybrid frequency. The magnetic field variations in the Pc3-4 range are also observed at the edges of the plume region.

We present the relation between amplitude of the EMIC waves, the plasma density, and the occurrence of Pc3-4 wave, and discuss the amplification mechanism of EMIC waves.

地球放射線帯での高エネルギー電子消失において，電磁イオンサイクロトロン (EMIC) 波動は重要な現象の一つである．EMIC 波動による粒子の散乱は，放射線帯のスロット領域形成に寄与する可能性があるとも言われている．放射線帯ダイナミクスへの EMIC 波動の寄与を明らかにするために，いつどこで振幅の大きい EMIC 波動が励起し粒子と相互作用するか理解することが重要である．

2013 年 6 月 29 日の 1110UT から約 30 分間，約 3Re(GSE 座標) の場所で，2-6Hz のプロトンバンド帯 EMIC 波動が Van Allen Probe A (VAPA) の EMFSIS 磁場観測によって観測された．このイベントは 2013 年 6 月 27 日に始まった磁気嵐の回復時に生じ，1123UT と 1130UT に振幅が 10nT まで大きくなった．その振幅の増大と同時に，VAPA はプルーム領域を通ったことが upper hybrid frequency からわかった．さらに，Pc3-4 帯の磁場変動がプルーム領域の端で観測された．

今回の発表では，EMIC 波動の振幅と，プルーム領域，Pc3-4 波動との関係を議論する．

Statistical analysis of plasmaspheric EMIC waves

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Electromagnetic ion cyclotron (EMIC) waves in the inner magnetosphere are important since EMIC waves cause the pitch angle scattering of ring current ions as well as relativistic electrons of the radiation belts. Although the spatial distributions of EMIC waves have been investigated by several spacecraft such as CRRES, THEMIS and AMPTE/CCE, there have been little studies on plasmaspheric EMIC waves. We investigate statistically EMIC wave data using the Akebono/VLF measurements. The plasmaspheric EMIC waves tend to be distributed at lower L-shell region (L˜2) than the slot region. There are no significant MLT dependences, which are different from the EMIC waves outside the plasmapause. The plasmaspheric EMIC wave frequencies depend on the equatorial cyclotron frequency, suggesting that the plasmaspheric EMIC waves are not propagated from high L-shell but generated near the equivalent L-shell magnetic equator. This result is consistent with the result of the dependence of resonance energy. Using the in-situ thermal plasma density measured by the Akebono satellite, we estimate the resonance energy of energetic ions, and the resonance energies of the plasmaspheric EMIC waves are few tens keV to ˜1 MeV. The results indicate that the ring current and radiation belt ions may contribute the generation of the plasmaspheric EMIC waves.

In-situ observations of nonlinear wave particle interaction of electromagnetic ion cyclotron waves

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A direct measurement method for the electromagnetic wave and space plasma interaction has been suggested by a computer simulation study [Katoh et al., 2013], so-called Wave Particle Interaction Analysis (WPIA). We apply the WPIA to rising tone electromagnetic ion cyclotron (EMIC) waves (so-called EMIC triggered emissions), of which the generation mechanism is essentially the same as the chorus emissions. We use THEMIS observation data (EFI, FGM, and ESA) for this analysis. We calculate (1) the dot product of the wave electric field and the velocity of energetic protons (6.92 keV), W_{int}, (2) the dot product of the wave magnetic field and the velocity of energetic protons (6.92 keV), W_{Bint}, and (3) the phase angle between the wave magnetic field and the perpendicular velocity of the energetic protons. The values of (1) and (2) that we obtained from the THEMIS data indicate the existence of the resonant currents inducing the nonlinear wave growth and the frequency change, respectively. We find the negative W_{int} and positive W_{Bint} at the growing phase of the triggered emission as predicted in a nonlinear wave theory [e.g. Omura and Nunn, 2011, Shoji and Omura, 2013]. The histogram of (3) shows the existence of the electromagnetic proton holes in the phase space generating the resonant currents. We also perform a hybrid simulation and evaluate the WPIA method for EMIC waves. The simulation results show good agreement with the in-situ THEMIS observations.

周波数遷移を伴う波動スペクトルの統計処理のための自動抽出法

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Automatic detection of waves with rising/falling tone frequencies for their statistical analysis

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Statistical analysis of relations between waves with rising/falling tone frequencies and ambient plasma plays an important role to study wave-particle interaction. In order to detect such waves from a huge dataset, we developed an automatic detection method by using template matching. The detection is based on differences of wave spectrum because it depends on generation and propagation mechanisms. We applied the developed method to the huge waveform dataset of Akebono to detect chorus emissions that is typical waves with rising/falling tone frequencies. In the template matching, parametric chorus-like shapes are used as templates and the matching is based on a cross-correlation. As a result, plenty of chorus emissions are successfully detected.

コーラスや VLF トリガードエミッションに見られるような周波数遷移を伴うプラズマ波動の励起において，非線形な波動粒子相互作用が重要な役割を果たしているといわれる．こうした波動と背景プラズマ (観測領域) との関連を実観測データで統計的に調査をするには，大規模なデータセットからこうした波動だけを自動抽出することが重要である．1989 年に打ち上げられたあけぼの衛星は 25 年という長期に渡り運用が続けられており，搭載機器の一つである WBA (Wide-Band Analyzer : 広帯域 VLF 波動受信器) では 14 kHz までの電界もしくは磁界の波形を優れた時間継続性と周波数分解能で観測しており，数 10 TB の大容量データとして蓄積されている．本研究では，このデータにテンプレートマッチングを適用することで，周波数遷移を伴う波動の自動抽出を試みた．あけぼの衛星では数多くの波動が観測されているが，特にコーラスを対象とした．

コーラスはスペクトログラムにおいて，周波数上昇や下降を伴う孤立したエレメントとして現れるという定性的な特徴が知られており，波動が現れる周波数帯や周波数上昇率，継続時間は生成・伝搬過程に依存する．このような特徴を持つコーラスに対して，スペクトログラムを画像として見てテンプレートマッチングを適用することで自動抽出を行った．具体的には，観測スペクトログラムに対しエレメントの周波数変化を模擬したテンプレートをずらしながら走査させ，各点における類似度を算出した．類似度にはいくつかの尺度があるが，本解析では相互相関係数を用いた．相互相関係数は，強度の定数倍の変化や強度平均の違いがあっても同じ類似度が得られるという特徴を持つ．テンプレートは，コーラスの様々な生成・伝搬条件に対応するため，各エレメントにおける縦方向の長さ (周波数帯)，横方向の長さ (継続時間) の 2 つのパラメータに対して 2 次元のガウス分布を使用して強度分布を作成し，さらに角度 (周波数上昇率) のパラメータにあわせて分布を傾けることでスペクトログラム上でのコーラスの強度分布を再現した．テンプレートマッチングの結果，形状の異なる様々なコーラスを抽出できることが確認された．

今後は，本手法により抽出したコーラスについて，形状パラメータと背景プラズマとの関係を統計的に調査する予定である．

新型ワンチップ・プラズマ波動スペクトラム観測装置の設計開発

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The development of the new type of the spectrum plasma wave receiver

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We have been attempting the miniaturization of plasma wave receiver by using the analog ASIC (Application Specific Integrated Circuit). Plasma wave receiver is categorized into the waveform type receiver and the spectrum type, and they are complementary to each other. We already succeeded in realizing 6 channels of the waveform receiver on the 5 mm x 5 mm chip. The waveform receiver has the advantage in observing nonlinear phenomena because it has the capability of detecting phase information of waves. However, it has several disadvantages. They are: large size of its output data due to the direct sample of waves, and the poor S/N originated from the frequency wideness of the observation band. To compensate these disadvantages, we propose the new spectrum receiver.

The new spectrum receiver is composed of analog circuits that is realized by ASIC and CPU or FPGA. Plasma waves picked up by sensors are limited in the specific frequency bands and amplified. Then, the band-limited signal is A/D-converted and applied to the FFT by CPU or FPGA. The band limit frequency, gain of the receiver amplifiers and sampling frequencies change synchronously step by step. By repeating this process, the receiver can obtain whole spectrum. In current design, the 1st band is between 1 Hz and 1 kHz, the 2nd is between 1 kHz and 10 kHz, and the 3rd is between 10 kHz and 100 kHz. In this presentation, we introduce the design of the new spectrum receiver in detail. We also introduce the measurement result of the analog component for the receiver.

宇宙空間におけるプラズマ波動現象の測定のために様々な理学ミッションにおいて、プラズマ波動受信器を利用した測定が行われてきた。プラズマ波動受信器は高性能なアナログ回路が必要であり、それらをディスクリート部品から構成しているために、大型となってしまうことが問題となっていた。我々は、プラズマ波動受信器について、特定用途向け集積回路 (ASIC) を利用した小型化を行ってきており、現在までに 6ch 分の波形捕捉型受信器を 5mm x 5mm のワンチップに収めることに成功している。しかし、波形捕捉型受信器においては、「波形をそのままサンプリングするためにデータ量が多く連続観測が難しい」、「広帯域のままで増幅を行うために高い S/N が実現できない」、などの欠点がある。このような欠点を補うためには、スペクトル型のプラズマ波動受信器を別途用意するのが従来からのやり方であったが、スペクトル型プラズマ波動受信器は、更に、電子回路規模が大きくなるため、波形捕捉型受信器で得られた波形を、衛星機上で FFT 計算することによってスペクトルを得て地上に伝送する、という手法がとられるようになっている。しかし、波形捕捉型受信器の観測波形から数値計算して得られるスペクトルを観測する以上、波形捕捉型がもつ上述の欠点をそのまま引き継いでいることになる。そこで、我々は ASIC による波形捕捉型受信器のアナログ回路を利用した上で、上述の欠点を克服した新型のスペクトル受信器を提案する。

この新型スペクトル型プラズマ波動受信器は ASIC によるアナログ回路と CPU や FPGA によるディジタル信号処理を組み合わせた方式である。アナログ回路部は、ASIC により超小型化された状態で実現される。それは、主に帯域制限用バンドパスフィルタ、メインアンプ、アンチエイリアシングフィルタ及び、制御回路から構成される。各フィルタ及びアンプはそのカットオフ周波数やゲインを制御回路からの信号により可変となる構造をしている。バンドパスフィルタのカットオフ周波数を変化させることで測定対象である 1 Hz〜100 kHz をある帯域を、いくつかの狭い帯域 (バンド) に分けることができるようになる。そしてバンドの切換に同期して異なるゲインで増幅を行い、異なる周波数でサンプリングを行う仕組みを実現させる。サンプリングした信号は CPU、FPGA により FFT をかけることでスペクトルを得る。このような処理を各バンドで行うことで対象とする周波数帯全体のスペクトルを測定する。現在の設計においては 1 Hz〜100 kHz を 1 Hz〜1 kHz、1 kHz〜10 kHz、10 kHz〜100 kHz の 3 つのバンドで測定することを想定しており、このようにバンド数が少数であるため、従来の細かく掃引するスペクトル型受信器に比べ、高い時間分解能を実現できる。

本発表では、この新型スペクトル型受信器について、アナログ回路部の設計及びこれまでに試作された各コンポーネントの測定結果について述べる。

Relativistic electron acceleration by whistler chorus elements including de-trapping effect: GEMSIS-RBW simulations

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Test-particle simulations have been done to demonstrate relativistic electron flux enhancement by whistler chorus elements propagating parallel to the magnetic field line of the dipole model. In this model it assumes that the whistler chorus elements periodically enhanced at the magnetic equator propagate both northern and southern directions simultaneously. These elements interact with electrons moving along the magnetic field line, and change their pitch angle and energy. The test-particle simulations show that, in identically coherent whistler chorus element, some electrons are nonlinearly trapped and are strongly accelerated through the relativistic turning acceleration process. On the other hand, by assuming that the condition for the trapping is broken in the element during the nonlinear trapping, electrons are de-trapped and the nonlinear effect in electron acceleration is hidden behind a diffusive process. Resent observational results indicate that whistler chorus element consists of several sub-packets of whistler waves which cause the de-trapping during electron nonlinear acceleration. Our simulations suggest that sub-packets structure in the whistler chorus element controls the efficiency of relativistic electron enhancement.

WPIA手法に基づくホイッスラーモードコーラス放射による高エネルギー電子のピッチ角散乱過程の定量評価について

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Simulation study of WPIA for direct measurements of pitch angle scattering of electrons by chorus emissions

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Pitch angle scattering of energetic electrons by chorus emissions is one of significant wave-particle interactions in the Earth's magnetosphere. A number of previous studies showed that electrons with the kinetic energy of a few keV to tens keV are scattered by whistler-mode waves and that the scattered electrons precipitated into the atmosphere cause diffuse aurora and/or pulsating aurora. However, recent studies suggest that the dominant wave mode contributing to the precipitation should be different depending on the local time and radial distance in the magnetosphere. In addition, the location where the efficient pitch angle scattering occurs and the physical process controlling the characteristic time scale of aurora have not been identified yet. Therefore, direct measurements of wave-particle interactions would contribute the thorough understanding of the pitch angle scattering in the magnetosphere.

Fukuhara et al. (2009) proposed a new instrumentation called Wave-Particle Interaction Analyzer (WPIA), which measures a relative phase angle between a wave magnetic field vector and a velocity vector of each particle and calculates the energy exchange between waves and particles. The WPIA is able to directly detect wave-particle interactions in space plasmas and will be installed on the ERG satellite of JAXA/ISAS. In the present study, in addition to the energy exchange proposed by Fukuhara et al. (2009), we propose the direct measurement of the pitch angle scattering of resonant particles by plasma waves via the WPIA by computing the Lorentz force of wave electromagnetic fields acting on each particle.

We apply the proposed method to results of the one-dimensional electron hybrid simulation reproducing the generation of whistler-mode chorus emissions around the magnetic equator [Katoh and Omura, 2007]. By using the wave and velocity vectors of 180 - 220 keV electrons obtained at fixed observation points assumed in the simulation system, we analyze the averaged Lorentz force acting on each particle in the whole simulation time, corresponding to 20,000 gyro periods. We use the time and pitch angle resolutions of 500 gyro-periods and 1 degree, respectively, for the analysis.

In the result of the analysis, we obtain significant values for electrons in the kinetic energy and pitch angle ranges satisfying the cyclotron resonance condition with the reproduced chorus emissions. The obtained value is three times larger than the magnitude of perturbations in other pitch angle ranges. We compared the result of the analysis with the temporal variation of pitch angle distributions and wave spectra observed at fixed points in the simulation. While the pitch angle distribution varies similarly in both hemispheres, the obtained Lorentz force is only significant in the pitch angle range corresponding to the electrons moving northward (southward) in the southern (northern) hemisphere, indicating the pitch angle scattering of electrons by pole-ward propagating chorus emissions. The results of the present study demonstrate that the proposed method enables us to identify the location where the pitch angle scattering occurs in the simulation system. We also discuss the method to evaluate the ambiguity of the WPIA measurement by referring the integration time, pitch angle resolution and number of particles necessary to obtain statistically significant values as well as an example of the application of the proposed analysis method to evaluate long-time variation of the distribution function of energetic/relativistic electrons including the nonlinear effect of wave-particle interactions by chorus emissions.

プラズマ波動による電子のピッチ角散乱は、地球磁気圏において重要な波動粒子相互作用の一つである。数 keV から数十 keV の運動エネルギーを持った電子は、ホイッスラーモード波動と広いピッチ角範囲でサイクロトロン共鳴条件を満たし、相互作用することが知られている。相互作用の結果としてピッチ角散乱を受けロスコーン角よりも小さいピッチ角を持つに至った電子については、地球大気に降り込みディフューズオーロラあるいはパルセイティングオーロラを発生させる原因となりうるというシナリオが数々の研究において示唆されている。一方で、近年の研究によりピッチ角散乱を担う波動のモードが磁気地方時や動径方向距離によって異なっている可能性が示唆されており、また、パルセイティングオーロラに特徴的な周期的発光の時間スケールを決める物理過程が同定されていないなど、未だ解明されていない問題が多く残されている。従ってピッチ角散乱の直接観測は、磁気圏内の波動粒子相互作用がどこでいつどのように生じているかを詳細に理解するために重要である。

波動粒子相互作用解析装置（Wave-Particle Interaction Analyzer; WPIA）は Fukuhara et al. (2009) により提唱された新しいタイプの観測装置である。WPIA は波動の電磁場ベクトルと粒子の速度ベクトルの相対位相角を測定することにより、様々な物理量を演算・出力する装置である。WPIA は宇宙空間プラズマにおける波動粒子相互作用を直接的に観測することが期待され、JAXA/ISAS の次期磁気圏探査衛星 ERG に搭載される予定である。本研究では Fukuhara et al. (2009) により提案された波動一粒子間のエネルギー授受量を表す物理量に加えて、ピッチ角散乱を直接計測するための物理量を提案する。具体的には個々の粒子の受けるローレンツ力の平均値あるいは積算値を計算する手法である。

本研究ではまず、コーラス放射の生成過程を再現したシミュレーションに対して新たに提案する WPIA 手法を適用し解析を行った。シミュレーションでは１次元ハイブリッドコードが用いられ、赤道付近でコーラスが発生し、両磁極に向かって振幅を増幅させながら伝搬する様相が示されている [Katoh and Omura, 2007]。シミュレーション中に複数の擬似観測点を置き、その場所を通過した高エネルギー電子の速度ベクトルと電磁場ベクトルを用いて、シミュレーション時間全体に相当する 20000 ジャイロ周期にわたってローレンツ力の解析を行った。解析に用いる電子のエネルギー帯は 180 - 220 keV とし、時間分解能およびピッチ角分解能はそれぞれ 500 ジャイロ周期、1 度を想定して解析を行った。

解析の結果、発生するコーラス放射の周波数帯とサイクロトロン共鳴条件を満たすエネルギー・ピッチ角範囲に対応する電子が、ピッチ角散乱される方向に有意なローレンツ力を受けることを、本研究で提案する手法により定量的に評価できることが示された。解析により得られたローレンツ力の大きさは、共鳴条件から外れるピッチ角を持つ粒子が示す値の変動に対して、３倍程度の値をとる事が示された。さらに、粒子のピッチ角分布の時間変動を北半球・南半球それぞれにおいて計測したところ、ピッチ角分布の変化する範囲や大きさは両半球でほぼ同様な結果となることに対して、ローレンツ力の解析では北半球（南半球）の地点では南（北）向きの波動の共鳴条件に対応するピッチ角範囲においてのみ有意な値が得られた。これは、赤道方向に運動する高エネルギー電子が、極方向に伝搬するコーラス放射によってピッチ角散乱を受けた事を示している。これらの結果から、本研究で提唱する新たな WPIA 解析手法によって、どのような粒子が・どの領域で・どの程度の強さのピッチ角散乱を受けるかを、直接且つ定量的に同定すること可能であることが示された。本発表では今回の解析手法の統計的不確定性の見積もりを行い、実際の観測において統計的に有意な値を得るために必要な時間分解能・ピッチ角分解能・積算個数などを議論するとともに、コーラス放射による非線形効果を含めた分布関数の長時間発展を評価する応用例についても報告する。

Van Allen Probes衛星データを用いた、ULF波動分布と経度方向波数についての解析

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ULF wave distribution and azimuthal wave number observed by Van Allen Probes

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Ultra low frequency (ULF) waves in the magnetosphere are generated by various processes. Understanding their distribution in the inner magnetosphere is important to estimate their energy source and generation processes. In this study, we investigate the spatial distribution of ULF wave occurrence at L=3-7, for toroidal, poloidal, and compressional modes, in Pc3-5 frequency ranges using magnetic field data obtained by Van Allen Probes from October 2012 to July 2014. We find that azimuthal Pc5 waves are frequently observed on the dayside, in particular on the morning side. Poloidal Pc4-5 waves appear on the dayside and in the pre-midnight region.

Azimuthal wave number of ULF waves is an important parameter. Most of the previous studies estimated the azimuthal wave number by using ground magnetometers or HF radars. Since the observation of azimuthal wave number in space needs multiple satellites, there are only a few studies that estimated the azimuthal wave number. Van Allen Probes consist of two spacecraft, and we can calculate the azimuthal wave number from a phase difference of ULF waves observed by these probes. We choose events in which the azimuthal and radial separation between satellites are within 2.5 degrees and 0.1 Re, respectively. We find about 30 events in which satellites satisfy the above criteria and simultaneously observe ULF waves. One of the events shows the azimuthal wave number of about -190 in pre-midnight at L˜5.8.

In the presentation, we will discuss the results in detail in comparison with past studies.

昼間側 Pi 2 地磁気脈動の電離圏等価電流分布

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Distribution of equivalent ionospheric currents associated with dayside Pi 2 pulsations

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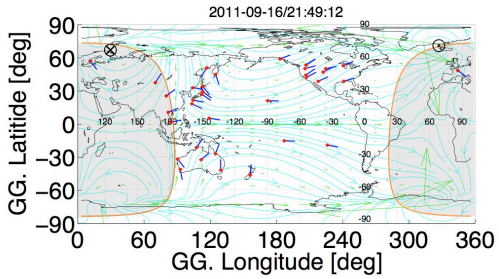
Pi 2 pulsations are defined as transient dumping oscillations of geomagnetic fields with period between 40 and 150 sec. The source (or energy source) of Pi 2s is believed to be located in the magnetotail because they mainly occur accompanied with onset of nightside auroral intensifications. Pi 2 pulsations are even observed on the day side ground, which means they can propagate to the dayside region from the nightside region. The latitudinal profiles of amplitude and phase difference of dayside H-component Pi 2s supported that electric fields from high-latitude region penetrate equatorward, and then drives the zonal ionospheric current enhanced at the dayside equator due to the Cowling effect. However, it is unclear how the dayside zonal ionospheric current are connected with the source electric field to ensure current continuity. In this study, we investigated the distribution of equivalent ionospheric currents associated with Pi 2 fluctuations on the day side using magnetic data from globally distributed ground-based stations. The equivalent current vectors were determined by rotating the filtered horizontal magnetic field vector by an angle of 90 degrees clockwise. Oscillating equivalent currents flowed equatorward (poleward) in the prenoon sector and poleward (equatorward) in the postnoon sector. Around the noon, the equivalent current flows in the zonal direction. The meridional component of equivalent currents in the prenoon sector is larger than in the postnoon sector and configuration of currents appears to be asymmetric. We also numerically estimated the distribution of ionospheric currents produced by the SCW-like pair of FACs around the midnight. The distribution of the simulated ionospheric current is consistent with that of equivalent currents derived from observed magnetic fields. We conclude that the oscillating ionospheric current system driven by nightside FAC oscillations is the dominant source of dayside Pi 2 pulsations.



Swarm衛星と地上低緯度地磁気観測点で観測されたPi2地磁気脈動の比較

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Comparisons of Pi2 pulsations observed by the Swarm satellite in the upper ionosphere and on the ground at low latitudes

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At the time of substorm onsets, Pi2 pulsations at low latitudes on the ground are observed at all local times. However, some studies show no evidence for dayside Pi2 pulsations in the magnetic field data observed by satellites at low latitudes within the plasmasphere [Takahashi et al., 2005; Teramoto et al., 2008; 2011]. Using the magnetic field data from the CHAMP satellite in the F region ionosphere and from the low-latitude ground stations, Sutcliffe and Lühr (2010) found that daytime Pi2 pulsations do not occur on CHAMP while nighttime Pi2 pulsations are observed simultaneously on CHAMP and at low-latitude ground stations. In order to clarify generation mechanisms of low-latitude Pi2 pulsations, we need to investigate the spatial structure of low-latitude Pi2 pulsations in the ionosphere.

In this study, we compared with Pi2 pulsations in the upper ionosphere and on ground at low latitude, using the magnetic field data observed by the Vector Field Magnetometer from the Swarm satellite and by the fluxgate magnetometers at Kakioka (KAK, 27.19 deg Geomagnetic latitude, 208.79 deg geomagnetic longitude) and San Juan (SJG, 28.20 deg Geomagnetic latitude, 6.10 deg geomagnetic latitude). The Swarm was launched on November 2013 and consists of the three identical satellites (Swarm-A, -B, and -C) in polar orbits. The Swarm-A and Swarm-B satellites move side by side at an altitude of 450 km and the Swarm-C at an altitude of 530 km. These multiple measurements are suitable for the spatial analysis of ionospheric Pi2 pulsations.

Pi2 pulsations started at 16:16 UT on 8 December 2013. At both Swarm-A and -B satellites the pulsations observed in the North component until 16:23 UT. The periods of the pulsations are 60 s and the amplitude are about ˜1 nT. During 7-min interval of the event the satellites moved from 20 deg to -10 deg in geomagnetic latitude and about 1.0 hours in magnetic local time (MLT). At KAK, which is located at about 01 MLT, the H component indicates nearly identical oscillations to Pi2 pulsations at both Swarm-A and -B. These observed characteristics were a consequence of the cavity mode resonance. We will show several Pi2 events observed by the Swarm satellite at different local times and discuss the possible mechanisms of low-latitude Pi2 pulsations.

IHM法とAPGM法によるFLR周波数、磁気圏プラズマ密度、FLR共鳴幅の緯度依存性解析：CARISMA・MAGDAS同時観測データへの適用

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IHM and APGM methods applied to sumultaneously observed data of CARISMA and MAGDAS: Latitude dependence of FLR parameters

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http://denji102.geo.kyushu-u.ac.jp/denji/staff/kawano/kawano.html

The Improved Hodograph Method (IHM below) and the Amplitude-Phase Gradient Method (APGM below) are both applied to data from two ground magnetometers latitudinally separated by ~100km and yield the field-line-resonance (FLR) frequency and the resonance width as functions of the latitude; from the FLR frequency we can estimate the magnetospheric plasma mass density, and from the resonance width we can estimate the damping rate of FLR, which is related to how much of the FLR-generated ULF waves are absorbed by the ionosphere.

The both methods apply FFT to the two magnetometers' data, and calculate the amplitude ratio and the cross phase from the two stations' data as functions of the frequency. From there the two methods use different approaches: IHM fits a curve to the obtained ratio (as a complex number including both the amplitude ratio and the cross phase) on the complex plane to separate out the non-FLR signal in the data, while APGM assumes that the obtained amplitude ratio and cross phase include the FLR signal only and obtains the FLR frequency and the resonance width in an algebraic manner.

In this paper we apply the two methods to simultaneously observed data from three ground station pairs of North-American MAGDAS and CARISMA, and discuss the latitude and longitude dependence of the FLR frequency and the resonance width.

Improved Hodograph Method（以下 IHM）と Amplitude-Phase Gradient Method（以下 APGM）は、どちらも、同じ子午線上で緯度方向に～100 ｋｍ離れた 2 つの地上磁力計のデータのみから、磁力線共鳴（field-line resonance、以下 FLR）周波数と共鳴幅を同じ子午線上の緯度の関数として求める方法である。FLR 周波数からは、その子午面上の磁気圏プラズマ密度を推定する事が出来る。また、磁気圏で FLR により生じた ULF 波動の電離層によるエネルギー吸収率が大きい程、共鳴幅も大きい。

IHM と APGM はどちらも、まず磁力計データをフーリエ変換し、2 つの観測点での磁場変動の振幅比と位相差を、周波数の関数として求める。その後、APGM は、得られた振幅比と位相差はどちらも FLR 信号しか含まない、と仮定して、そのデータから FLR の式の解析解を使って FLR 周波数と共鳴幅を求める。一方 IHM は、得られた振幅比と位相差から複素比を求め、それを複素平面にプロットし（これを hodograph という）、それに曲線をフィッティングする（signal-noise separation の一手法）事によって、得られたデータ中から FLR 信号のみを抜き出す。

本発表では、北米の MAGDAS 観測点 WAD（磁気緯度 61.3、磁気経度 318.3 [度]）、CARISMA 観測点 WEYB（58.6、320.9）、LGRR（61.8、332.4）、PINA（60.0、331.8）、THRF（57.8、331.5）の同時観測データを用い、WAD － WEYB、LGRR － PINA、PINA － THRF の 3 ペアに IHM と APGM を適用する。そして、同じ子午線上の LGRR － PINA、PINA － THRF それぞれに IHM を適用して得られる FLR 周波数と共鳴幅の緯度分布が 2 つのデータセットで（期待通り）類似している事を示す。また、その FLR 周波数・共鳴幅の緯度依存性について議論する。更に、緯度は似た値だが経度の異なる WAD － WEYB と LGRR － PINA － THRF での同時観測で、FLR 周波数や共鳴幅の値が異なる事があると示し、その経度依存性について議論する。

Toward the establishment of scientific principle of M-I-T coupling: Alfven wave interaction with the weakly ionized ionosphere

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Interaction between the shear Alfven wave and weakly ionized ionosphere is discussed in the context of inductive Magnetosphere-Ionosphere-Thermosphere coupling.

The conventional equations of ionospheric electrodynamics, highly successful in modeling observed phenomena on sufficiently long time scales, can be derived rigorously from the complete plasma and Maxwell's equations, provided that appropriate limits and approximations are assumed. For example, an interaction between shear Alfven wave and ionospheric current system has been successfully described in terms of the reflection and mode conversion process at the

electrostatic Ohmic current layer, in which Hall and Pedersen conductivities are derived under stress balance equilibrium between Ampere force and frictional force by plasma-neutral collisions.

However this approach cannot describe dynamic developments inside the ionosphere or provide information about causal relations of MIT coupled variables. The verbal descriptions are intended to provide an intuitive understanding of results from calculations, but sometimes they go beyond their nominal purpose and are expanded into qualitative discussions of causal sequences and sometimes even of temporal developments, even though these are not really described by the conventional equations.

To correctly describe the inductive and dynamic process of MIT coupled system or perform verbal description of MIT responses, we need to explicate the generalized Ohm's law for determination of electric field, plasma motion of equation for evolution of plasma velocities, Faraday's induction law for evolution of magnetic field, and Ampere's law for distribution of current density.

In this study on the basis of causal sequence of the aforementioned inductive MIT coupling process, we try to understand the interaction process between shear Alfven wave and weakly ionized ionosphere, how Alfven waves propagate inside the ionosphere, how they attenuate by interaction to the neutral particles, how the field aligned current of wave modes bifurcate into the conducting current, and how the reflection process can be described by the causal relations inside the ionospheric E-region.

An automated procedure of sounding of the plasmasphere by the CRUX magnetometer array in New Zealand

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The plasmaspheric mass density derived from the ULF field line resonance (FLR) frequencies of two different magnetic shells (L=2.33 and 2.62 Re) have been monitored during a 3-month period (February-April 2013) using an automated cross-phase analysis of magnetic measurements recorded at the CRUX magnetometer array in New Zealand. We found the rate of FLR detection in the dayside can reach as high as 91% (2.33 Re) and 98% (2.62 Re). The inferred equatorial plasma mass density follows the L-dependence of L^{-4}. We also present the result of an analysis of the depression and the refilling of the plasmasphere during geomagnetic storms.

ULF 波動をわずかに緯度の異なる地磁気観測点で観測し，クロススペクトル解析を行うことで，磁力線共鳴振動周波数を精密に得ることができる．こうして得られた周波数からは，磁気圏プラズマ質量密度を推定することができるので，近年，プラズマ圏のリモートセンシングを行った研究が多数報告されている．本研究では，共鳴振動周波数の同定手続きを自動化し，ニュージーランドに設置された CRUX magnetometer array (L=2.19-2.78 Re) のデータ解析を行ったので，その成果を報告する．現時点では，2013 年 2 月－ 4 月の 3ヶ月間のデータが解析され，二つの magnetic shells (L=2.33 と 2.62 Re) におけるプラズマ密度の統計解析が行われている．まず磁力線共鳴振動の検出率を，昼間 (8-16LT) に共鳴振動が検出されたか否かで調べたところ，検出率は 91% (2.33 Re), 98 % (2.62 Re) で，L 値の大きい観測点で検出率がやや高い傾向が見られた．推定されたプラズマ密度の中央値は~3000 amu/cc (2.33 Re) と~1800 amu/cc (2.62 Re) で L^{-4} の L 値依存性が見られた．解析期間中には複数の磁気嵐が発生しており，それに関連した密度の増減も見えていた．発表では自動化手法の有用性を示す例として磁気嵐中のプラズマ圏の depression と refilling の解析結果についても紹介する．

SuperDARN北海道-陸別第二HFレーダーが目指すサイエンス

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[1] 名大 STE 研; [2] 名大 STE 研; [3] -

Scientific objectives of the SuperDARN Hokkaido West radar

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The SuperDARN Hokkaido West radar is the second SuperDARN radar in Japan, and the 10th midlatitude SuperDARN radar in the northern hemisphere. It is the first northern midlatitude SuperDARN radar equipped with the function of STEREO mode, which enable us to monitor 2 beam directions simultaneously, thus to make 1-min two-dimensional and 1 to a few second one-dimensional observation at the same time. This mode is useful to the study of short time scale phenomena such as ULF waves, SC-associated disturbances and substorm expansion onsets. Scientific objectives, together with the latest status, of the SuperDARN Hokkaido West radar will be presented.

SuperDARN 北海道-陸別第二 HF レーダー (以下、第二レーダーと呼称) は、日本国内に設置する二番目の中緯度 SuperDARN レーダーである。順調にいけば、2014 年 10 月中旬に設置が完了し動作を開始する予定である。現在 (2014 年 8 月) 既存の北海道-陸別第一 HF レーダーを含めて北半球に 9 基の中緯度 (設置場所が磁気緯度約 50 度以下)SuperDARN レーダーが稼働しているが、第二レーダーは北半球中緯度 SuperDARN レーダーとして初めて STEREO mode(2 周波数を使用することにより、同時に 2 ビーム方向の観測を可能とする) を実装するレーダーであり、1 分分解能の広域 2 次元観測と特定のビーム方向を 1〜数秒の時間分解能で観測する高時間分解能観測を同時に実施することができる。この機能を用いて、ULF 波動や SC、サブストーム開始等に伴う短時間スケールの現象を詳細に捉えられると期待できる。また、来年度打ち上げ予定の内部磁気圏観測衛星 ERG との様々な共同観測が期待できる。講演においては、第二レーダーを活用して目指すサイエンス、および可能ならば初期観測結果について報告する予定である。

ジオコロナ撮像装置LAICAの開発状況

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Development status of geocoronal hydrogen Lyman Alpha Imaging CAmera (LAICA)

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Exospheric hydrogen atoms resonantly scatter solar ultraviolet radiation, causing an ultraviolet glow. It is so called geocorona. To date, various observations of the geocorona have been made. The previous observational results suggest that geocorona extends to an altitude of about 20 R_E. Recently, abrupt temporary increases (from 6% to 17%) in the total number of hydrogen atoms in the spherical shell from a geocentric distance of 3R_E to 8R_E have been recorded during several geomagnetic storms. However, the relation between geomagnetic activity and hydrogen exosphere is still unclear.

Past observation of the geocorona has mainly been performed using earth orbiters. Therefore, several low altitude (~8 R_E) observations have been made. However, the geocorona at high altitude can be observed only from the deep space at the geocentric distance of >20 R_E. There have been only a few observations, e.g., Mariner 5, Apollo 16, and Nozomi. Among them, only Apollo 16 had a 2-D imager. Its observational FOV was about 10 R_E and not wide enough for imaging the whole geocorona expanding to 20 R_E.

In this study, we are developing a LAICA (Lyman Alpha Imaging CAmera) instrument onboard the very small deep space explorer PROCYON, which will be launched in December 2014 with the Hayabusa 2 spacecraft. PROCYON will escape the earth and navigate interplanetary space. Our instrument can perform wide FOV (more than 25 R_E) imaging of the geocoronal distribution. If we can detect geocoronal distribution at high altitude, it will help understanding loss process of earth's atmosphere. The flight model of LAICA was completed. Calibration tests have now been conducted. All tests are scheduled to be completed in August. In this presentation, we will describe the scientific objectives of LAICA and report the results of flight model calibration.

地球外気圏に存在する水素原子は、特定の波長 (121.567nm) の太陽紫外放射を選択的に散乱することで光っており、地球全体を包む紫外グローを形成することからジオコロナと呼ばれている。過去の観測では高度約 20R_E にまで及ぶジオコロナが確認されている。ジオコロナの空間分布の特徴として、外気圏水素が反太陽方向に引き伸ばされ、密度が太陽方向よりも高くなるようなジオテイルと呼ばれる構造や、昼夜、南北、朝夕の非対称性などが知られている。最近では磁気嵐が発生した時刻に伴って、3~8R_E までの範囲に存在する水素原子数が 6~17%程度増加するという現象が確認されたが、その原因は未解明である。

過去の計画では地球周回衛星からの観測が主で、ジオコロナの広がりに対して低高度 (~8R_E) の観測が多く行われてきた。一方、高高度のジオコロナ分布を捉えるためには地球から十分離れ、ジオコロナの外から観測を行う必要がある。しかし観測例は極めて少なく、そのような観測を行ったのは Mariner 5、Apollo 16、のぞみの 3 例だけである。その中で、Apollo 16 のみ 2 次元イメージャを搭載しており、ジオコロナの初の撮像が行われたが、観測視野は 10R_E 程度までとなっている。

本研究では 2014 年 12 月に打ち上げが予定されている、超小型深宇宙探査機 PROCYON に搭載予定のジオコロナ撮像装置 LAICA の開発を行っている。地球を脱出して惑星間空間を航行するような軌道に乗る探査機からであれば、地球周回衛星よりも広い観測視野 (25R_E 以上) でジオコロナの全球分布を捉えることが可能となる。これにより高高度における水素原子散逸過程について、低高度の観測により構築された理論を検証する。さらに、磁気嵐が起きた時に、周回衛星に比べて高い時間分解能 (約 2 時間) でジオコロナの全球分布の変動を捉えることで、外気圏への水素原子供給過程と、大気散逸過程に対する太陽活動の影響を調べる。打ち上げ後約 1 週間で観測を開始し、その後約 3 か月間観測を実施する予定である。現在はフライトモデルの製作が完了し、環境試験や較正試験を実施している。本発表では LAICA の概要、較正試験結果について報告する。

Estimating the latitudinal dependence of plasmaspheric helium ion density based on data assimilation of the IMAGE/EUV data

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The latitudinal dependence of the plasma density along magnetic field lines is very important property that controls wave propagation and other physical processes. In analyzing EUV data taken from the IMAGE satellite, each EUV image only provides the information on a two-dimensional structure. Thus, it is basically difficult to resolve the latitudinal profile from a single EUV image. However, if multiple EUV images, which were taken from a different direction due to the motion of the satellite, are used, it would be possible to estimate the latitudinal profile. We have developed a data assimilation technique for estimating the temporal evolution of helium ion density distribution from a sequence of the IMAGE/EUV data. Since this data assimilation technique uses multiple EUV images, we can obtain the information on the latitudinal profile of helium ion density by combining a maximum likelihood approach. We will discuss how the latitudinal profile can be estimated and present some preliminary results.

内部磁気圏高エネルギー電子生成に対するサブストームの影響に関する数値実験

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Numerical experiments on the impacts of substorms on energetic electrons in the inner magnetosphere

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The reconstruction of the outer radiation belt is the object of a controversial argument. The previously suggested processes of the reconstruction can be divided into two groups; the internal acceleration hypothesis and the external source hypothesis. For both hypotheses, substorms are thought to play an important role in the reconstruction of the outer radiation belt. Hot electrons are rapidly injected into the inner magnetosphere during substorms, which provide free energy for wave growth of whistler mode chorus waves. Electrons are accelerated to the MeV range through Doppler shifted cyclotron resonance, or relativistic turning acceleration with whistler mode chorus waves. Relativistic, or sub-relativistic electrons may also be transported inward by strong, impulsive electric field, probably contributing to the reconstruction of the outer belt directly. In general, to distinguish the two hypotheses is problematic. Although no direct evidence has been proven to show that energy is certainly transferred from waves to electrons, some characteristic manifestations have been used to be a proxy of the internal acceleration, that is, characteristic pitch angle distribution (for example, flat-top distribution), hard energy spectra, and earthward gradient of the phase space density at constant adiabatic invariants. The purpose of this study is to test if these manifestations are necessary condition or sufficient condition for the internal acceleration, and to illuminate the relative contributions from the two hypotheses to the reconstruction of the outer belt. We have solved bounce-averaged drift transport equations under the electric and magnetic fields given by the recently developed global MHD simulation. We reproduced the sequence of a substorm, and determined onset as a sudden decrease in the AL index and a sudden increase in the ionospheric conductivity (a proxy of aurora). Near the onset, a strong electric field is formed in the inner magnetosphere in a longitudinally narrow region with a thickness of the order of earth radius (Re), which rapidly transported relativistic electrons inward. Simultaneously, keV electrons were also injected inward, which may become a seed of relativistic electrons. Temperature anisotropy becomes large near the leading edge of the injected hot electrons. As the plasmapause shrinks, the ratio of the plasma frequency to the cyclotron frequency becomes small outside the plasmapause, which may favor the growth of chorus waves. We estimated the evolution of the phase space density of electrons due to the interaction with chorus waves under the assumption that the wave amplitude is small. We will demonstrate the results of numerical experiments on the energy spectrum, pitch angle distribution and radial gradient of the phase space density of energetic electrons for the purpose of identifying physical processes responsible for the observable signatures and providing a guide to understanding the abrupt reconstruction of the outer radiation belt.

放射線帯外帯の再生過程には内部加速と外部供給という大きく二つの考え方があり、議論の対象となってる。サブストームは両過程において重要な役割を担うと考えられている。サブストーム時、熱い電子が磁気圏尾部から流入し、ホイッスラーモード・コーラス波動を励起するための自由エネルギーを提供する。波動粒子相互作用の結果として電子はMeV レンジまで加速されることが指摘されている。これは内部加速の考え方である。一方、相対論的、準相対論的電子がサブストーム時に印可された電場によって内側に輸送され、外帯を作るという指摘がある。これは外部供給の考え方である。一般的に両過程を観測的に区別することは大変困難である。波のエネルギーが電子に転移する現場はまだ直接捉えられておらず、内部加速過程の直接的な証拠は得られていないが、flat-top 型など特徴のあるピッチ角分布や、硬いエネルギースペクトル、地球方向の位相空間密度勾配は内部加速過程の間接的な証拠とされている。 本研究の目的は、内部加速過程の間接的な証拠とされるこれらの特徴が内部加速過程の必要条件か十分条件かを明らかにすること、放射線帯外帯再生に対する両過程の相対的な寄与を明らかにすることにある。グローバル MHD シミュレーションを用いてサブストームを再現し、得られた電場と磁場のもとバウンス平均ドリフト輸送シミュレーションを用いて内部磁気圏電子の輸送・加速・消失過程を解く。境界条件を様々に変えた数値実験を行い、両過程で発現が期待される電子の分布関数の特徴を抽出し、放射線帯外帯再生に対する両過程の相対的寄与について考察する。

Van Allen Probes 衛星搭載 RBSPICE 粒子検出器による磁気嵐中の高エネルギー水素および酸素イオンの複数点観測

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Multi-point observations of energetic protons and oxygen ions during magnetic storms by the Van Allen Probes RBPICE instrument

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We examine short time-scale (shorter than 30 min) enhancements of energetic (greater than 50 keV) ions in the inner magnetosphere (L less than 6) during magnetic storms. This study focuses on the storm main phase on June 1 and 7, 2014 during which two Van Allen Probes spacecraft dwelled with a small separation (dL less than 1, dMLT less than 0.5 h). Analyzing ion data with high energy, angular resolution and mass information provided by the RBSPICE instrument, we study temporal, spectral, and pitch angle evolution of proton and oxygen ions to identify the spatial scale of plasma population injected from the plasma sheet and occurrence/lack of non-adiabatic acceleration in the inner magnetosphere.

RBSPICE detects ions with the energy range of ~50 to ~1000 keV, with high energy resolution. In the region at the radial distance greater than 3 RE, where RBSPICE has been in nominal operation, the magnetic field strength ranges from ~100 to ~1000 nT. Thus, the first adiabatic invariant (mu) of ions monitored by RBSPICE is below ~2 keV/nT near the inner most point of the nominal operation and reaches ~20 keV/nT around the Van Allen Probes apogee.

In this study, we analyze temporal and spatial variations of ion phase space density for different mu values, pitch angles/second invariants, and species. We also compare the results with storm events on August 4 and August 27, 2013, when the Van Allen Probes experience larger satellite-to-satellite separation: ~2 RE in the radial direction and ~2 hours in the MLT direction.

Rapid enhancement of energetic oxygen ions in the inner magnetosphere during substorms

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Satellite observations show that energetic (greater than 100 keV) O^+ ions are rapidly increased in the inner magnetosphere during substorms. The ultimate source of O^+ ions is the Earth's ionosphere, so that O^+ ions must be accelerated from ˜eV to 100s keV somewhere in the magnetosphere. A fundamental question still arise regarding why O^+ ions are accelerated and transported to the inner magnetosphere. We simulated substorms under two different solar wind conditions by using the global MHD simulation developed by Tanaka et al. (2010, JGR). The solar wind speed is set to be 372 km/s for Case 1, and 500 km/s for Case 2. In both cases, the MHD simulation result shows that the dawn to dusk electric field is enhanced in the night side tail region at greater than 7 Re just after the substorm onset. In particular, the electric field in the inner region (˜7 Re) is highly enhanced by the tension force because of relatively strong magnetic field together with curved field lines. The strongest electric field takes place near the region where the plasma pressure is high. We performed test particle simulation under the electric and magnetic fields for Cases 1 and 2. O^+ ions are released from two planes located at 2 and -2 Re in the Z direction in the tail region. O^+ ions released at the two planes represent outflowing stream of O^+ ions escaping from the Earth. The distribution function at the planes is assumed to be drifting Kappa distribution with temperature of 10 eV, the density of 10^5 m^{-3}, and the parallel velocity given by the MHD simulation. In total, around a billion of particles are traced. Each test particle carries the real number of particles in accordance with the Liouville theorem. After tracing particles, we reconstructed 6-dimensional phase space density of O^+ ions. We obtained the following results. (1) Just after substorm onset, the differential flux of O^+ ions is almost simultaneously enhanced in the region where the electric field is strong. (2) The kinetic energy increases rapidly to 120 keV for Case 1, and 200 keV Case 2 in the inner magnetosphere. (3) On the dayside, the pitch angle anisotropy of O^+ ions increases with radial distance. We will discuss the acceleration processes and generation mechanisms of pitch angle anisotropy of O^+ ions in more detail, and the overall contribution to the ring current.

電離圏へのエネルギー流入と酸素及び水素イオン流出との経験的関係式の太陽天頂角依存性

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Solar zenith angle dependence of empirical formulas between energy inputs to the ionosphere and O+ and H+ ion outflows

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Recent satellite observations and simulations have clarified that plasma outflows play an important role in abrupt changes in the ion composition in the plasmasheet and ring current during geomagnetic storms. Statistical studies by *Strangeway et al.* [2005] and *Brambles et al.* [2011] indicated that fluxes of ion outflows are correlated well with soft electron precipitation (precipitating electron density and electron density in the loss cone), and DC and Alfvenic Poynting fluxes using the data obtained by the FAST satellite near the cusp region in the dayside during the 24-25 September 1998 geomagnetic storm. To evaluate the correlations for H^+ and O^+ ions separately, we performed statistical studies using the ion composition data in addition to the ion, electron, and field data obtained by the FAST satellite during January 1998 and January 1999. The longer dataset enables us to identify empirical formulas between outflowing O^+ and H^+ ion fluxes and precipitating electron densities, DC and Alfvenic Poynting fluxes in a wide solar zenith angle (SZA) range (45-145 degree). These empirical formulas would be useful for global magnetospheric simulations as the boundary conditions. Under dark conditions, H^+ ion fluxes increases with increasing precipitating electron density, but not as much as those do under sunlit conditions. The precipitating electron density that corresponds to the H^+ ion flux of ~10^7 /cm^2/s (mapped to 1000 km altitude) decreases with increasing SZA. This SZA dependence is less clear for O^+ ions as compared with H^+ ions. The empirical formulas between outflowing O^+ and H^+ ion fluxes and DC and Alfvenic Poynting fluxes are not so strongly affected by SZA. Under sunlit conditions, the flux O^+ ions tends to be larger than that of H^+ ions, while H^+ ions tend to become dominant under dark conditions. Intense ion (especially O^+ ion) outflow events (number flux larger than 10^8 /cm^2/s mapped to 1000 km altitude) mostly occurred under sunlit conditions or near the terminator.

Significance of results of plasma wave sounder experiments by Akebono/PWS

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Plasma wave sounder experiments have been conducted by Stimulated Plasma Wave experiment (SPW) subsystem of Plasma Wave and Sounder experiments (PWS) on board Akebono (EXOS-D) satellite in the topside ionosphere and plasmasphere [Oya et al., JGG 1990]. The sounder experiments have two main purposes: One is the remote sensing of the topside ionosphere including polar region and inner plasmasphere, and another is active experiments by the stimulation of plasma waves in space. Both of them have been successfully conducted by the SPW subsystem of Akebono/PWS. As for an example of previous studies of Akebono/PWS sounder experiments, Kodama and Ono [2002] revealed the presence of the plasma bulge structures in the polar region of the topside ionosphere from the analyses of ionograms. The observation results of the radio wave echoes at an altitude of 6,000 km suggest the feature of the duct propagation at the boundary of plasmasphere. The new finding of f_{D0}, corresponding to the n=0 case of the sequence of diffuse plasma resonances (SDPR) [Oya, JGR 1970; Tadaoka and Oya, 1998], provides the strong evidence to support the weak turbulence theory as the generation mechanism of SDPR. In this paper we revisit the results of plasma wave sounder experiments by Akebono/PWS and discuss the significance of sounder experiments for the study of the polar region of the topside ionosphere and for the investigation of the plasma physics in the process of stimulated wave-particle interactions in space.

あけぼの衛星のPWS観測データによるプラズマ圏構造の変動の統計解析

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Statistical analysis of variations of the plasmasphere observed from the Akebono PWS

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The plasmasphere is a region of cold and dense plasma surrounding the Earth. The plasma density in that region and its vicinity, i.e., the inner magnetosphere is an important parameter for understanding the dynamics of the radiation belts. Variations of the plasmaspheric density distribution have not been completely clarified. In this context, we conduct statistical analyses on the variations of the plasmasphere and plasmatrough, using electron density data derived from plasma wave observations by PWS experiments on board Akebono satellite from 1989 to 2002. The averaged field-aligned density gradient in the inner plasmasphere (L = 2.1-2.3) is less dependent on the solar cycle, while that in the outer plasmasphere (L = 4.2-4.7) is strongly affected by the solar activity. We also investigate possible processes of the plasmaspheric refilling and its solar-cycle dependence. The daily variations of the field-aligned density distribution after geomagnetic disturbances are defined in such a way that the Kp-index becomes to be smaller than or equal to 3 after the geomagnetic active period (Kp-index greater than 3). The density depression is not found at L smaller than ~3. While the density at L larger than ~4 is found to decrease at an altitude above ~3000 km, and to take ~3 days to be refilled. Currently, solar cycle variations are not necessarily clear. We will further investigate refilling processes associated with stronger geomagnetic disturbance, and more detailed temporal variations to clarify the presence of solar-cycle dependence. Averaged variations in the plasmaspheric density during geomagnetic storms driven by CMEs are also studied with superposed epoch analyses and reported.

プラズマ圏は電離圏起源の冷たいプラズマが宇宙空間に湧き上がり、閉じた磁力線に閉じ込められて形成される領域であり、地磁気活動に応じてその密度構造が変化することが知られている。プラズマ圏の密度分布は内部磁気圏の物理過程にとって重要であり、多くの衛星で観測されているものの、その構造の太陽活動依存性やリフィリング過程などは完全には解明されていない。本研究では、あけぼの衛星の PWS 観測によって得られた 14 年間のプラズマ圏電子密度データを用いて、プラズマ圏電子密度分布とその太陽活動度による変動、地磁気擾乱後のリフィリングとその太陽活動依存性について、統計解析を行った。その結果、密度分布に関してはプラズマ圏深部（L = 2.1-2.3）では太陽活動による変動は小さく、他方、外部プラズマ圏（L = 4.2-4.7）では平均の密度勾配が太陽活動によって大きく変動することが明らかになった。また、プラズマ圏リフィリングの過程とその太陽活動依存性については、磁力線に沿った密度分布の磁気擾乱後の時間変化に関して、superposed epoch analysis を行い 24 時間ごとの変動を調べた。その際、磁気擾乱によって Kp 指数が 3 を超えた後に Kp 指数が 3 以下になった時刻を原点とした。本解析より、L=3 より内側では密度変化は見られず、L=4 より外側において、高度約 3000 km 以上の領域で密度が減少し、擾乱が収まってから 3 日程度で密度が回復することが判明した。現時点においては、顕著な太陽活動依存性は見えていないが、今後、より詳細な時間変化や、大きな磁気擾乱時のリフィリング過程についても解析を実施し、太陽活動依存性の有無を調べる予定である。さらに、CME による磁気擾乱中のプラズマ圏密度の時間変化についても superposed epoch analysis を行い、その結果を報告する。

小型化を目指した熱的・超熱的イオン分析器の開発

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Development of thermal-suprathermal ion analyzer

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Satellite observations have revealed that ions such as H^+ and O^+ escape from the Earth's ionosphere to the magnetosphere. Typical temperature of these ions is cold (˜0.1 eV) in the ionosphere, but they are observed with energies of 1-10 eV in the magnetosphere. The acceleration process is not fully understood. In order to understand the escape processes of ions, in-situ plasma measurements are considered to be effective tools. However, it is not easy to observe these cold ions in general, since, in the Earth's magnetosphere, a spacecraft is positively charged in sunlight. One of the solutions to reduce the effect of spacecraft charging is installation of a boom onto the spacecraft. One can compensate the spacecraft potential when the plasma particle analyzer is mounted on the boom to which the voltage corresponding to the spacecraft potential is applied. Note that, Debye length should be shorter than the boom length in this case.

We have been developing the thermal-suprathermal plasma analyzer which is light enough to be mountable on top of the boom. The sensor consists of two parts. One is top-hat type electrostatic energy analyzer (ESA). The other is time-of-flight (TOF) system that measures velocity of incoming particles. Particle mass (mass-per-charge) can be deduced when velocity and energy-per-charge of the particle are determined.In order to measure the low-energy particles with ˜0.1eV, we have to apply a very low voltage (a few tens of mV) to the ESA electrode in case of conventional electrostatic analyzers which are optimized for particle energies of keV range. However, it is not easy to apply such a low voltage with enough stability. Our idea is to expand the gap between ESA electrodes. The wide gap provides: (1) the applied voltage to ESA electrode becomes higher, (2) analyzer sensitivity is improved, and then, analyzer size can be smaller. TOF technique measures appearance interval of two different signals. One is generated by secondary electrons emitted from an ultra-thin carbon foil at the passage of incoming ions. The other is generated by the incoming ions themselves. It is important to control the trajectories of the secondary electrons to be focused on detector area near the symmetrical axis, since areal size of the detector should be small in order to keep the analyzer size small.

An overview of the analyzer and its performance will be presented.

過去の衛星観測によって地球電離圏イオンが磁気圏に流出していることが知られている．電離圏イオンは 0.1eV 程度の熱的なエネルギーを持つが，磁気圏ではそれを超える 1-10eV 程度のエネルギーで観測されており，この間の加速過程については未だ十分に理解されていない．この加速過程の理解のためには，粒子観測器による直接観測が有効である. しかしながら, 地球磁気圏では衛星が正に帯電する場合が多く，このような低エネルギーイオンが観測器に到達できないという問題がある．この問題の解決案の一つとして衛星から伸ばしたブームの先端に観測器を付けることを考えている．

本研究では，ブームの先端に取り付け可能な小型軽量化を重視した熱的・超熱的イオン分析器の開発を進めている．この観測器は入射イオンのエネルギー分析を行うトップハット型静電分析部 (ESA) と，装置内のイオンの飛行時間から質量を計測する Time-Of-Flight(TOF) 型の質量分析部で構成されている．この観測器構成は従来から精力的に開発されてきた keV 帯プラズマ粒子を観測対象とした観測器と同等であるが，これらの観測器では ˜0.1eV の粒子を計測する場合に極板に数十 mV 程度の低電圧を与える必要がある．このような低電圧を安定的に印加することは簡単ではない．このため，我々は極板間の距離を広げることで解決を試みた．これにより以下の二点の利点が有る．(1) 必要な掃引電圧を高くすることができ，従来と同程度の精度で掃引制御が可能．(2) 小型でありながらも，感度を維持することが可能．また TOF 型質量分析器では，イオンが質量分析器入り口に設置された炭素超薄膜に通過した際に発生する二次電子を Start 信号として扱い，イオン自身を Stop 信号として扱う．二次電子の軌道を対称軸付近の検出位置に収束させることで，観測器の小型化を図っており，現在はそれに最適な電極設計を進めている．

本発表では熱的・超熱的イオン分析器の概要とその性能について報告する．

かぐやで観測されたオーロラキロメータ波の偏波のレイトレーシングによる解析

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Ray tracing analyses of the polarizations of auroral kilometric radiatin (AKR) observed by Kaguya near the Moon

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In KAGUYA (SELENE) LRS[1], WFC-H[2] observes wave spectra in 1kHz-1,000kHz and various plasma waves like Auroral Kilometric Radiation (AKR), electron plasma waves, and broadband electrostatic waves have been observed. This system can observe wave polarizations by two pairs of dipole antennas. We have analyzed the AKR polarizations.

The polarization of AKR is defined with respect to the magnetic field from a view point of plasma waves. On the other hand, the polarization is observed with respect to the propagation direction. Both polarizations depend on the source hemisphere. Kaguya moves behind the Moon every rotation. The occultations of AKR radiated from the Earth occur. When only one hemisphere can be seen due to the occultation, the source hemisphere is identified and the polarization can be measured correctly. This result is also useful when both hemispheres are seen after the occultation. We will show some cases including when the polarizations are identified and both polarizations are observed without occultation and their interpretation based on ray tracing.

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月周回衛星「かぐや（SELENE）」搭載 LRS[1] の WFC-H 波動観測装置 [2] では，1-1,000kHz の波動のスペクトルを観測でき、オーロラキロメータ波（AKR），電子プラズマ波，広帯域静電波などが観測され，周辺プラズマ環境のモニターにもなっている。本装置は二対のダイポールアンテナを用いた偏波観測が可能であり、AKR の偏波解析を行ってきた。

AKR の偏波観測を行っても、プラズマ波動で言う磁場方向に対する偏波と観測される進行方向に対する偏波の関係は，源の半球により逆転する。かぐやは地球からの電波である AKR の観測中に、周回ごとに月の背面に入るが、その間地球の一部が隠れる時間がある。掩蔽観測は，AKR が、片半球しか見えていない時間帯に受かっているかどうかで源の半球が特定でき、同時に偏波も観測できる。この情報は、両半球が見える状態になっても、解釈のあいまいさをなくすことができる点で有意義である。掩蔽を用いて偏波を特定でき，両半球が見える状態で両偏波が観測された例を含む観測結果とレイトレーシングによる解釈を示す。

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Role of fast flow channels in aurora and tail-inner magnetosphere interaction

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Plasma transport in the plasma sheet and auroral oval is known to involve a significant amount of transient fast flows that are longitudinally localized. Recently, using a combination of the THEMIS satellites, all-sky imagers and SuperDARN radars, those fast flow channels are found to play a crucial role in triggering substorm auroral onset, whose pre-onset sequence has been in strong debate in the community for decades. Those pre-onset flows originate from the far downtail several minutes before the auroral onset, and can also be seen as auroral poleward boundary intensifications (PBIs) and subsequent roughly north-south aligned auroral streamers that reach the equatorward portion of the auroral oval. The precursor aurora was found very commonly (˜80% of events) in THEMIS ASI observations.

Furthermore, we found that those fast flows are a critical element of tail-inner magnetospheric interactions. Some of those flow bursts penetrates into the inner magnetosphere, and increases the ring current pressure, EMIC wave intensity, and proton auroral luminosity. This process can occur in a few tens of minute time scale, which is much more rapid than by slowly varying convection driving, and suggests that flow bursts from the plasma sheet give rapid modulation of the ring current. When SuperDARN echoes are available, SAPS flow enhancements were also seen to occur as equatorward (earthward at the equator) extension of the fast flow channels. Those responses in the inner magnetosphere and subauroral ionosphere can be seen both during non-storm and storm-time events, suggesting that flow bursts in the plasma sheet have a high impact on plasma and energy transport into the inner magnetosphere and subauroral ionosphere.

脈動オーロラと相対論的電子マイクロバーストの統一モデル

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Common characteristics of the pulsating aurora electrons and relativistic electron microbursts

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We investigate whether the pulsating aurora and relativistic electron microbursts are caused by a common process. Using Reimei and SAMPEX satellite data, we investigate characteristics of the pulsating aurora electrons and relativistic electron microbursts, respectively. Reimei satellite reveals that the pulsating aurora is caused by repetition of tens keV electrons and the internal modulations with a few Hz exist inside the precipitation. Beside intermittent precipitations of a few keV electrons, the stable precipitation of low energy electron ~1 keV is simultaneously observed. SAMPEX satellite confirmed the pulsation of relativistic electron microbursts and the internal modulations embedded in the microburst. We simulate the pitch angle scattering of energetic electrons from ten keV to ~1 MeV, considering the propagation of whistler mode waves along the field line. As a result of the simulation, the pulsation and internal modulations of electrons are caused by the repetition of chorus bursts and rising tones, respectively, and those are commonly observed in both ten keV electrons (pulsating aurora) and relativistic electron microbursts. Upper band chorus waves cause the stable low energy electron precipitations. The results indicate that the propagating whistler mode chorus waves are the common process to cause both pulsating aurora and relativistic electron microbursts along the field line.

脈動オーロラは、数 keV~数十 keV の電子が間欠的に降り込んで引き起こされる現象である。一方、放射線帯外帯では、しばしばマイクロバーストと呼ばれる 1 秒以下の時定数でバースト的に MeV 電子が降りこむ現象が存在することが知られている。この両者の特性を詳しく調べるために、本研究では、れいめい衛星と SAMPEX 衛星のデータ解析と波動粒子相互作用によるピッチ角散乱のシミュレーションによる研究を行った。れいめい衛星、SAMPEX 衛星の観測から、脈動オーロラを引き起こす降下電子と、放射線帯外帯の MeV 電子のマイクロバーストには、次のような共通点があることが明らかになった。1) 周期数秒で間欠的な降り込みが起こる。2) 降り込みの内部には、周期数 Hz の内部変調が存在する。このような特徴が、磁気圏赤道面で発生し、その後高緯度に伝搬するコーラス波動と電子との相互作用によるものとの仮説をたて、シミュレーション計算を行ったところ、コーラス波動によって、keV から MeV に至る広いエネルギー帯の電子降下が起こることが示されるとともに、また、周期性や内部変調についても、観測結果と整合的な結果が得られた。この結果は、従来別々のものと考えられてきた脈動オーロラと放射線帯の MeV 電子のマイクロバーストが同一のものであることを示すものである。

A proposal to the energy budget in the auroral ionosphere: Challenge from thermospheric winds in the pulsating aurora

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Pulsating aurora is a typical phenomenon of the recovery phase of magnetic substorm and is frequently observed in the morning sector. The widely accepted generation mechanism of pulsations in precipitating electrons is related to wave-particle interactions around the equatorial plane in the magnetospheric tail. This mechanism is completely different from the discrete-arc case, which generates high-energy auroral electrons by the inverted-V type potential structure in the magnetospheric acceleration region. This potential structure induces the perpendicular electric field. The electric field is mapped down to the ionosphere, and enhances the Pedersen current as the ionospheric closure current. Since the perpendicular electric field directly relates to the Joule heating rate and the Lorentz force, thermal and kinetic energies in the thermosphere are locally increased in the vicinity of the arc rather than the inside, resulting in wind variations in the thermosphere. However, this scenario cannot be simply applied to the pulsating-auroral case because of the completely different mechanism of the auroral-electron generation, and we have believed that large energies are not dissipated in the pulsating aurora and there should be no obvious wind variations in the thermosphere. However, we found thermospheric-wind variations in the pulsating aurora during simultaneous observations with a Fabry-Perot Interferometer (557.7 nm), several cameras, and incoherent-scatter radars. This is a significantly important finding in evaluating our understanding of the energy budget in the substorm recovery phase. As mentioned above, the Joule heating process and the Lorentz force play important roles for thermospheric-wind variations. While the both cases need enhancements of the perpendicular electric field, we well know that a typical level of the convection electric field is too low to generate the wind variations in a same level as the observed in the pulsating aurora. Thus the observed wind variation is a clear evidence that our estimation of the dissipated energy in the recovery phase has been underestimated. This presentation will summarize our measurements showing several events of the pulsating aurora, in particular focusing on the energy budget in the magnetosphere-ionosphere-thermosphere coupled system.

Compound auroral microphysics

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Auroral microphysics still remains widely unexplored because of the limitation of high-speed imaging. Cutting-edge ground-based optical observations using sCMOS cameras with a large data storage recently enabled us to continuously observe the fine-scale morphology of aurora at magnetic zenith for a variety of rapidly varying features, such as flickering, pulsating modulation, and arc packets etc. According to the spatiotemporal scale, the fine-scale auroral morphology is important to understand the fundamental wave-particle interactions, and is potentially useful to diagnose the plasma environment of magnetosphere-ionosphere coupled system. We report two interesting examples of unexpected combinations of fine-scale rapidly varying auroras. Localized flickering aurora appeared during the instability growth of an arc, which may represent the efficient energy dissipation of Alfvenic and quasi-static activities as operated at the midnight open/closed boundary. Another example shows a pulsating modulation nearby flickering rays in the middle of surge in the pre-midnight sector, which may indicate the close relation of enhancement of Alfven waves and efficient loss of energetic particles.

Extremely fast auroral morphology beyond the ULF range: new ground-based experiment using sCMOS cameras

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Small-scale and high-speed auroral morphology is important because fundamental physical processes behind the wave-particle interaction can be visualized. The smallest and fastest spatiotemporal variation of auroras is tens of meters and a fraction of a second, which appears especially during intense auroral activities, and is potentially useful to diagnose the plasma environment of magnetosphere-ionosphere coupled system. The purpose of this study is to find the fastest aurora and to understand the formation mechanism of the small-scale and high-speed auroral morphology. Two identical imaging systems were installed at Poker Flat Research Range (PFRR) in Alaska from February to April 2014. A highly sensitive sCMOS camera with the imaging sensor of 2048 x 2048 pixels and the narrow field of view of 15 x 15 degree enable us to identify the smallest auroral structure. The field of view approximately corresponds to 26 km x 26 km at 100 km altitude, and the spatial resolution is ˜52 m when 4 by 4 binning is used. One system uses a sub-array option to enhance the sampling rate up to 1000 frames per second. We used RG665 sharp cut filter only for the sub-array imaging. A major criterion to select the events for this study is more than 15 KR auroral emissions of 557.7 nm at the magnetic zenith. We found a total of 16 nights satisfying the above criterion. About a half of the events are associated with moderate or intense magnetic storms. As the most distinctive examples, it is found that flickering auroras show ˜30 Hz oscillations on February 20, 2014 during storm-time substorms, which are beyond the ULF range (<5-10 Hz). The minimum Dst index was -86 nT at ˜13 UT (˜1.5 MLT), and the AE index exceeded 1000 nT. Pulsating auroras with ˜20 Hz modulations were also captured in the postmidnight sector. Based on such initial results from February to April 2014 data sets, we are developing a new camera system with two major improvements. One is to improve the recording synchronism between two sCMOS cameras by using a GPS clock. The second is the ”active burst mode” to store huge amounts of data observed only when intense auroras appeared overhead, applying an automatic detection technique by using a Nikon DSLR camera with fish-eye lens. The new combined system of the sCMOS camera and the Nikon DSLR camera will be installed at PFRR in the next winter season to statistically investigate the occurrence distribution of the small-scale and high-speed auroras for the first time.

南極用無人オーロライメージャの開発

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Development of unmanned aurora imager for Antarctica

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There are numbers of all-sky aurora imagers operated in Antarctica. However, there are still huge gaps between their field of views (FOVs). Based on successful experience of low-power unmanned magnetometer observation in Antarctica, we are developing unmanned aurora imager (UAI) to fulfil these gaps in aurora observation. Useful application of the UAI is to track the motion of conjugate auroras. We have found from our long-term observation that the conjugate aurora sometimes moved hundreds of km azimuthally in tens of minutes. We are planning to install UAIs at Soer Rondane Mountains and Amundsen Bay, 700km to the west, and 550km to the east of Syowa Station, respectively. FOV of these imagers, together with that of Syowa, extends more than 2000km in geomagnetic east-west direction, and very useful for tracking the motion of conjugate auroras.

Power consumption of the UAI system is designed to be less than 20W, and it is supplied from three sets of wind generator, Rutland FM910, four 60W solar panels, and 800Ah battery. Watec TV camera is used for the all-sky imager, and the image is taken 1 frames/s. GPS TEC and 3-component flux-gate magnetometer observations are also made in this system. The data are recorded in SD card and the summary data, including keogram of aurora image, will be transferred to Japan daily via Inmarsat BGAN telephone. We are planning to start the field observation from 2016.

脈動オーロラの発生領域内外における電磁場の特性

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Characteristics of pulsating aurora at the boundary region

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Pulsating auroras (PA) are common phenomena, which are observed universally during the recovery phase of substorm in the auroral and subauroral zones. But, even today, generation mechanism of fundamental characteristics of pulsating aurora, such as, their periodicity (e.g., a few seconds to a few tens of second including higher frequency of >3 Hz), their shapes (e.g., patch and band), and their motion (e.g., standing and propagating) are not understood. Conjugate observations onboard satellites and on the ground are important method to examine such fundamental characteristics of pulsating aurora. We examined some selected pulsating auroral events, which obtained onboard THEMIS spacecraft and THEMIS ground-based all-sky camera network.

We found following signatures of optical, particle, field and wave at the onset and during pulsating aurora; 1) All pulsating aurora associate with high-energy (>5 keV) electron flux enhancement, 2) Quasi-periodic modulation of DC electric field, cold electron flux and ELF waves sometimes show well correlation with visible pulsating aurora observed on the ground, 3) DC electric fields perform quasi-periodic fluctuation, which show good correlation to pulsating aurora in most of PA events, 4) Electrostatic ELF wave (<30 Hz) perform quasi-periodic fluctuation, which show good correlation to pulsation aurora (on 3 March 2011 event), 5) Electrostatic ECH waves are more correlating to pulsating aurora than that magnetic chorus waves are, 6) Not all pulsating aurora associate with ELF/VLF chorus wave enhancement, 7) Pitch angle of cold electron distributes to field-aligned, 8) There are very few evidences to identify a quasi-periodic modulation of high-energy electron flux, which may be directly corresponding to pulsating aurora.

Such evidences suggest that DC Electric Field and Cold Electrons may play more important role to generate pulsating aurora than chorus wave. We will discuss the role of DC electric field, cold electron and ELF waves for the generation of pulsating aurora.

脈動オーロラは 5kV 以上の高エネルギー降下電子フラックスの変調によって起こされていることが明らかになっている。しかし、高エネルギー電子フラックスが何故準周期的な変調を起こすかの直接的な要因は未だに検証されていない。この変調機構を解明する上で、衛星-地上同時観測は重要である。

磁気圏赤道面付近に位置している THEMIS 衛星群と地上全天カメラネットワークとの同時観測により、脈動オーロラにともなう粒子・電磁場・波動の特性について、以下のことが明らかになってきた。

1）全ての脈動オーロライベントは 5 keV 以上の高エネルギー電子フラックスが増加している時に起こっている、2）脈動オーロラの準周期的な変調に対応する DC 電場と 10eV 以下の低温電子フラックスの準周期的変動が頻繁に観測され、両者は良い相関を示す、3）この低温電子フラックスと DC 電場の準周期的変動は低周波電磁コーラス波動（Lower-band electromagnetic chorus wave）と静電的な電子サイクロトロンハーモニック波動（electrostatic Electron Cyclotron Harmonic wave: ECH wave）の準周期的な強度変動と一対一の良い対応を示すことがある、4）ただし、全ての脈動オーロラがコーラス波動や ECH 波動の出現に対応しているわけではない、5）低温電子フラックスのピッチ角分布は磁力線の方向に沿っており、電離圏起源であることを示唆している。

これらの特性をさらに明確にし、準周期的な変調の要因を明らかにするために、脈動オーロラの発生境界領域を THEMIS 衛星が通過した際における、領域の内外における DC 電磁場、低温電子フラックス、電磁波動などの準周期的変動に注目して、そのイベント解析を試みた。その結果、DC 電場、300Hz 以下の静電波動、そして、10eV 以下の低温電子フラックスが脈動オーロラに対応する準周期的な変動を起こしていた。一方、コーラス電磁波動や ECH 波動の準周期的な変動は認められなかった。

本講演ではこの脈動オーロラ領域の通過イベントに関する詳細な報告と脈動オーロラの発生機構に関する議論を行う。

サブストーム発達過程におけるプロトンオーロラと電子オーロラの関係： 昭和基地地上観測

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Relationship between proton and electron auroras during a course of substorm evolution: Ground-based observation at Syowa Station

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National Institute of Polar Research (NIPR) has been constructing an auroral optical observation system at Syowa Station during the 8th project term of 6 years of the Japanese Antarctic Research Expedition (JARE) program. Instruments categorized in the "Monitoring observation" are (1) 4 sets of All-sky monochromatic digital CCD imagers (427.8, 557.7, 485.0, 481.0 nm) and (2) All-sky color digital camera, and those categorized in the "Specific purpose observation" are (1) All-sky TV camera and (2) 8-color Scanning Photometer (SPM). Simultaneous observations with 2 electron and 2 proton CCD monochromatic imagers will be carried out in 2014. Interval of the 4 imagers are the same as each other, 15 sec, although the spatial resolution of the 2 proton imagers are reduced into 64x64, comparing with the full resolution of 512x512 of the electron imager.

Center (FWHM) wavelengths of the SPM are 482.5(0.6), 483.5(0.6), 484.5(0.6), 485.5(0.6), 486.5(0.6), 487.5(0.6),670.5(5.0), 844.6(0.6) nm. Scanning speed and sampling rate are 180 deg/10 sec and 20 Hz, respectively.

Using these electron and proton auroral data observed with all-sky imagers and scanning photometer, we would like to construct a comprehensive model of substorm including the information on energy characteristics of precipitating auroral electrons and protons.

極地研では、南極地域観測第　期6ヵ年計画の下、昭和基地でのオーロラ光学観測システムの整備を進めている。「モニタリング観測」機器としては、(1) 全天単色デジタル CCD イメージャ4 式（427.8, 557.7, 485.0, 481.0nm）と (2) 全天カラーデジタルカメラ、「一般研究観測」機器としては、(1) 全天 TV カメラと (2)8 色掃天フォトメータ、の導入を進めてきた。2014 年のシーズンには、電子オーロラ 2 波長（427.8, 557.7nm）とプロトンオーロラ 2 波長（481.0, 485.0nm）の全天 CCD イメージャ4 式による同時観測が実現出来ているので、その結果を中心に報告する。上記 4 式のイメージャの撮像間隔は 15 秒で共通にし、同じ時間分解能で電子オーロラとプロトンオーロラの空間分布を観測することを目的としている。微弱なプロトンオーロラを観測するため、プロトンイメージャについては、元々512x512 の画素数の CCD 出力に対し 8x8 のビンニングを行い、空間解像度を 64x64 に落としている。

8 色掃天フォトメータの波長構成（中心波長（半値幅））は、482.5(0.6), 483.5(0.6), 484.5(0.6), 485.5(0.6), 486.5(0.6), 487.5(0.6),670.5(5.0), 844.6(0.6) nm で、プロトンオーロラ（H β）のスペクトル用 6 波長と電子オーロラ用 2 波長からなる。掃天速度は 180 度/10 秒で、サンプリング速度は 20Hz である。

こうした全天イメージャと掃天フォトメータの電子オーロラ、プロトンオーロラ同時観測データにより、降下電子や降下プロトンのエネルギー情報も含んだ、オーロラサブストーム発達過程の総合的なモデルを構築するすることが最終的な目標となる。

電離圏アルヴェン共鳴波の伝播に伴う磁気赤道での渦形成

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Vortices in the magnetic equator generated by ionospheric Alfven resonant waves

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The purpose of the series of our studies is to clarify the auroral arc dynamics on the basis of magnetohydrodynamic (MHD) instabilities and their nonlinear evolution under the M-I coupling system. A three-dimensional MHD simulation of the feedback instability showed that Kelvin-Helmholtz type vortex structures are spontaneously excited in the magnetosphere [Watanabe, 2010]. A linear analysis of Alfven eigenmodes, considering the velocity cavities, revealed feedback properties of the field line and ionospheric Alfven resonances [Hiraki and Watanabe, 2011; 2012; Hiraki, 2013].

In this study, we performed three-dimensional nonlinear MHD simulations of shear Alfven waves in a full field line system with MI coupling and the steep Alfven velocity cavities. Nonlinear interaction of Alfven eigenmodes in the system showed various features: i) a secondary flow shear instability leading to vortices occurs at the magnetic equator, ii) trapping of the ionospheric Alfven resonant modes accelerates a cascade of auroral fine structures, and iii) waves emitted from the ionospheric cavity cause vortices and magnetic oscillations at the equator side. Essential features at the initial brightening of auroral arc could be explained by growth of the Alfven resonant modes, which are the nature of the field line system responding to a rapid change in the background conditions. We also report the progress of our model extension where electron inertia effects are included for the evaluation of parallel electric fields.

我々の一連の研究目的は、オーロラアークのダイナミクスを M-I 結合系における磁気流体不安定とその非線型発展という観点から体系化することである。フィードバック不安定の３次元計算により、磁気圏で Kelvin-Helmholtz 的な渦構造が自発的に励起することが示された [Watanabe, 2010]。アルヴェン固有モードの線型解析にて、その速度キャビティを考慮した際に現れる磁力線共鳴・電離圏共鳴モードのフィードバック安定性が明らかにされた [Hiraki and Watanabe, 2011; 2012; Hiraki, 2013]。

本研究では、３次元非線型 MHD 計算を行い、M-I 結合と急峻な速度キャビティを含めた全磁力線におけるシアアルヴェン波の振舞いを調べた。アルヴェン固有モード間の純粋な非線型相互作用から、以下のような特徴がわかった。i) 磁気赤道での渦形成に至る二次的なフローシア不安定が起こることを定量的に示した。ii) 電離圏アルヴェン共鳴モードがキャビティ領域にトラップされ、微細な水平構造の成長を促進した。iii) 電離圏キャビティから打ち出された波が磁気赤道での渦・磁場揺動を引き起こした。サブストーム時のオーロラアーク初期増光の裏にある性質は、以上のアルヴェン共鳴モードの成長によって説明できるかもしれない。それは、背景場の急激な変化に対する磁力線システムの自然応答だからである。我々は現在、平行電場の量的評価を行うため電子慣性を加えるモデル拡張を行っており、その進捗についても報告したい。

Substormオーロラの特徴：オンセット緯度における電離層渦電流の発達

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Characteristic properties of substorm auroras: A development of ionospheric loop currents at the onset latitudes

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The auroral signatures were examined for the event occurred at Yukon, Canada on 17 January 1994 from a pre-onset to the expansion using all-sky imager, ground magnetometer network, and plasma measurements at the conjugate magnetosphere. The results are summarized as follows:

1. The bead-like rippling and poleward expansion of aurora occurred following the fresh plasma transport from the plasma sheet to the geosynchronous orbit.

2. The plasma transport from the tail was associated with the earthward motion of the separatrix of drift trajectories (Alfven boundary). The earthward motion of the Alfven boundary was caused by the increasing convection electric fields.

3. The plasmas transported beyond the geosynchronous orbit in the equatorial plane eventually generate the loop currents in the ionosphere. The increasing size of the loop currents accompanied the poleward expansion of the aurora.

4. The loop current with the size of about 1000 km propagated eastward following the eastward propagation of Pi2 at low to mid latitudes.

References:
Saka, Hayashi, Thomsen (ANGEO, 2014)
Saka, Hayashi, Koga (JGR, 2012)

ユーコン準州 Dawson City でのオーロラをそのオンセット 40 分前から Expansion まで、All-sky imager、地上磁場ネットワーク、および磁気圏共役点に位置するロスアラモス衛星のプラズマデータを使い詳しく調べた。その結果をまとめると、

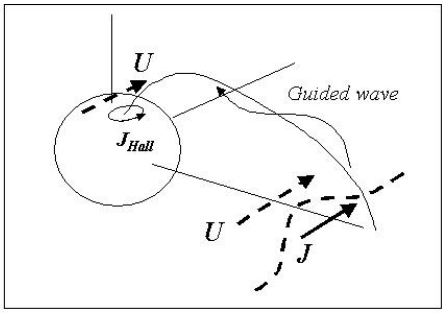
1. プラズマシートからのプラズマ供給に続きオーロラの活性化 (bead-like rippling, poleward expansion) が始まる。

2. プラズマの供給は、イオンおよび電子ドリフトの separatrix (Alfven boundary) が内側（地球側）へ移動する結果である。これは対流電場の増加を意味する。

3. プラズマは静止軌道を越えて地球側に供給され、電離層には渦電流が発達する。渦電流のサイズの増大に合わせオーロラの Poleward Expansion が観測される。

４. 差し渡し 1000 km に発達した渦は低緯度に Pi2 を伴いながら東へ伝播する。

参考文献：Saka, Hayashi, Thomsen (ANGEO, 2014)
Saka, Hayashi, Koga (JGR, 2012)



An ionospheric loop current triggered by an eastward propagating compressional input in the magnetosphere

惑星間空間磁場BY誘発シータオーロラに付随する単極性沿磁力線電流の観測

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Observation of unipolar field-aligned currents associated with interplanetary magnetic field BY triggered theta auroras

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It has been suggested that there are several mechanisms for theta aurora formation. One mechanism that is generally accepted is the one associated with interplanetary magnetic field (IMF) BY transition. When the sign of IMF BY switches during strong northward IMF, in the ionosphere, the duskside or dawnside plasma sheet is detached and the isolated plasma sheet drifts dawnward or duskward into the polar cap to form the theta aurora configuration [Cumnock et al., 1997; Chang et al., 1998; Kullen et al., 2002]. This formation process of the theta aurora is supported by global magnetohydrodynamic (MHD) simulations [Slinker et al., 2001; Kullen and Janhunen, 2004; Naehr and Toffoletto, 2004; Tanaka et al., 2004]. Watanabe et al. [2014], using MHD simulation, showed possible existence of a unipolar field-aligned current (FAC) system within the crossbar of the theta aurora. When the theta aurora is drifting duskward, the FACs are located on the dawnside boundary of the crossbar adjacent to the 'new' lobe and they flow away from the ionosphere. Conversely, when the theta aurora is drifting dawnward, the FACs are located on the duskside boundary of the crossbar adjacent to the 'new' lobe and they flow into the ionosphere. This unipolar FAC system drives nightside part of the round cell that causes the drift motion of the theta aurora crossbar. To the best of our knowledge, there has been no previous report on such a unipolar FAC system. The purpose of this paper is observational verification of the simulation results, using magnetic field and precipitating particle data obtained by DMSP satellites. On 24 October 2003, a well-defined stepwise change in IMF BY during strong (about 20 nT) northward IMF periods triggered a theta aurora. We confirmed from the DMSP data the presence of the very FAC system predicted by the Watanabe et al. [2014] MHD simulation.

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シータオーロラの成因には様々なものが考えられるが、広く受け入れられているものは惑星間空間磁場（IMF）BYの変動が形成の引き金になるというものである。強い北向き磁場が続いている時に、IMF BYが反転すると朝側あるいは夕側のオーロラオーバルからプラズマシートが分離し、極冠内にドリフトしてシータオーロラを形成する。この形成過程はグローバル電磁流体（MHD）シミュレーションでも再現されている [Slinker et al., 2001; Kullen and Janhunen, 2004; Naehr and Toffoletto, 2004; Tanaka et al., 2004]。Watanabe et al. [2014] はMHDシミュレーションにより、トランスポーラーアークに付随する単極性沿磁力線電流系の存在を示唆した。トランスポーラーアークが夕方にドリフトしていく場合には、沿磁力線電流は朝方の“新”ローブとの境界に現れ、電流の方向は電離圏から出る方向である。逆にトランスポーラーアークが朝方にドリフトしていく場合には、沿磁力線電流は夕方の“新”ローブとの境界に現れ、電流の方向は電離圏へ入る方向である。この単極性の沿磁力線電流は、トランスポーラーアークのドリフトを担うラウンド・セルの夜側部分の駆動源となる。このような単極性の沿磁力線電流の観測は過去に報告されたことはない。本研究は、DMSP衛星の降下粒子と磁場データを用いて、シミュレーション結果の検証を行うものである。2003年10月24日、強い（約20 nT）北向きIMFが続いている期間に、階段状にIMF BYの反転が起こり、シータオーロラが形成された。この事象の解析を行い、Watanabe et al. [2014] のシミュレーションで得られた沿磁力線電流系が実在することを確認した。

Response of the reverse convection to sharp IMF turnings: Observations from multi-spacecraft and ground magnetometer stations

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How strongly the dayside high-latitude convection is controlled by the orientation of the IMF for periods of the steady IMF is well established. However, the nature of the transition that the convection makes when the IMF changes sharply is still not fully understood. In the present paper, we report the characteristics of the transient nature of the reverse convection on the basis of observations from multi-spacecraft and ground magnetometer stations. During a period of northward IMF on 22 April 2006 the magnetic field observations from three ST-5 spacecraft identified distribution change in the polar cap field-aligned current which responds to a quick IMF turning from the purely northward orientation to the duskward orientation. At this time ST-5 flew over one of the Greenland magnetometer stations located near 1200 MLT. The analysis of the ground magnetic perturbations shows that the field-aligned current distribution, which is closely related to the reverse convection pattern, was changing gradually during about 10 min before reaching a steady state. When the steady state was going on, the IMF changed sharply from the duskward orientation to the dawnward orientation. Immediately after this IMF turning, three DMSP spacecraft (F13, F15, and F16) traversed the dayside polar cap in the northern hemisphere. The ion drift observation indicates that the polar cap convection changed from the clockwise circulation to the counter-clockwise circulation during about 10 min. The data from the Greenland magnetometer stations show that a transient state, i.e., deformation or reduction of the clockwise circulation started in the near-noon and postnoon sectors almost simultaneously when the ion drift consisting of the clockwise circulation is still seen in the prenoon polar cap by the DMSP spacecraft. We discuss the changing global patterns that occurred over the whole dayside polar cap during the course of the 10-min transient state for both cases.

Dawn-dusk asymmetry of transient convection associated with sudden impulses

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The previous statistical study using a large data set of SuperDARN (SD) observations showed that transient ionospheric flows associated with sudden impulses (SI) form vortex-like structures with the same polarity as those observed by ground magnetometers and that the substantial part of the flow structures are well extended to the night side across the terminator. Another interesting feature, which is focused on in this study, is that the flow structures seem to hold a dawn-dusk asymmetry with the polarity controlled by the combination of the polarity of SI and IMF-By. A detailed analysis of the SD observations reveals that the higher-latitude part of the flow structure is enhanced on the dusk (dawn) side for positive SIs (SI+) under negative IMF-By conditions and negative SIs (SI-) under positive IMF-By conditions (SI+ under positive IMF-By and SI- under negative IMF-By), respectively. To understand how the IMF-By-dependent asymmetry is introduced, we have performed a global MHD simulation of the solar wind-magnetosphere-ionosphere coupled system driven by abrupt rises or drops of the solar wind dynamic pressure for various parameters. The simulation result has qualitatively reproduced the same sense in dawn-dusk asymmetry of flow enhancement as that deduced by the SD statistics. The preliminary analysis suggests that the asymmetric flow enhancement is likely to be caused by the interaction between the pre-existing round convection cell and a pair of the transient convection vortices associated with SIs. Further it is shown by both the observation and simulation that there is always an asymmetry in flow intensity between the dawn and dusk convection cells induced by SIs, regardless of IMF-By polarity. We will discuss how this persistent dawn-dusk asymmetry is caused in SI-associated ionospheric convection in terms of the large-scale structure of field-aligned current and ionospheric conductance.

非ダンジェー対流駆動機構ー磁気圏物理学の新しいパラダイム

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Generation mechanism of the non-Dungey convection - A new paradigm of the magnetospheric physics

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The magnetosphere-ionosphere coupling convection is a core process from which all global magnetospheric phenomena like substorms, storms, steady magnetospheric convections, sawteeth events, sudden commencements, and theta auroras develop. However, only the schematic model proposed by Dungey (1961) has been accepted as a standard model of the convection. This fact is surprising compared with other precise researches of the magnetospheric physics like the reconnection. At the same time, this fact indicates backwardness of the magnetospheric physics compared with other Earth and planetary sciences like the atmospheric physics in which the physical process of the global circulation is well understood.

Tanaka (2003) proposed physical processes of the magnetosphere-ionosphere coupling convection based on precise global MHD simulation results. Although he established the physical processes inside the magnetosphere, there is still a missing link about transport of mass, momentum and energy from the solar wind to the magnetosphere in order to understand a driving mechanism of the magnetosphere-ionosphere coupling convection. After elucidating the transport mechanism, the magnetospheric physics becomes a precise science like the atmospheric physics. In order to investigate the driving mechanism of the convection - namely a driving mechanism of a dynamo for the Region 1 field-aligned current -, we pursue both transport of energy from the solar wind to the lobe via the cusp-mantle region and generation of a dynamo of the Region 1 field-aligned current in the context of conversion of energy in the cusp-mantle region based on a global MHD simulation. We first identify stream lines of the plasmas bulk flow pass from the solar wind to the lobe. The thermal energy in the magnetosheath is enhanced mainly by the solar-wind dynamic pressure. The electromagnetic energy from the cusp-mantle region also contributes to the enhancement. This enhanced thermal energy is converted to the field-aligned plasma bulk flows. This field-aligned bulk flow turns to be a perpendicular one due to the centrifugal force of a field-aligned flow on a curved magnetic field in the boundary between the magnetosheath and the lower-latitude side of the cusp. In the cusp-mantle region, decrease in the thermal energy due to plasma escape along field lines into the lobe induces a dynamo (the slow mode expansion). It is concluded that magnetic field merging (reconnection) in the dayside magnetopause does not play a direct role in driving the magnetosphere-ionosphere coupling convection. We also identify the magnetospheric energy convection in which the mechanical energy flux from the solar wind to the cusp-mantle region is partly converted to the Poynting flux returning to the dayside magnetopause.

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サブストームのエネルギー収支と磁気圏尾部のエネルギー輸送の評価

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An assessment of substorm energy budget and energy transport in the magnetotail

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In the present study we have quantitatively assessed substorm energy budget and energy transport in the magnetotail, based on the results of our previous observational studies. We have found that the magnetotail can provide sufficient energy for the substorm expansion, i.e., the ionospheric Joule heating and particle precipitation as well as the ring current injection. This contradicts what Akasofu [JGR, 2013] argued. Most of the energy of the near-Earth plasma sheet is transported by the net Poynting flux directly from the lobes, rather than by fast flows in the plasma sheet generated by near-Earth magnetic reconnection. We contend, however, that near-Earth magnetic reconnection drives the enhancement of the Poynting flux during the expansion phase, fully contributing to the substorm energy.

近尾部における電流密度分布の直接観測

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Statistics of current densities in the near-Earth tail

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Cross-tail current sheet and field-aligned current in the tail vary dynamically during substorms. This study examines spatial and temporal characteristics of current-density vectors using THEMIS multi-spacecraft observations in the near-Earth magnetotail. New technique is proposed to evaluate current densities without assuming any current sheet profiles, which uses 5-min averaged magnetic field measurements. Rich data set allowed us to infer the north-south profile of the cross-tail current sheet. On average, current sheet is found to be thick and bifurcated. Presumably owing to this non-uniform profile, local current density occasionally becomes very intense to compare with its ground (minimum) values. Origin of intense current densities and its relationship with substorms are discussed.

磁気圏尾部リコネクションの多重発生：テミス衛星による観測例

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Tailward leap of magnetic reconnection: A THEMIS case study

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A multiple-onset substorm is studied using observations of aurora and the magnetotail. In particular, the cause of the multiple auroral intensification and decay is discussed. A sequence of tailward then earthward flows was observed within 10 minutes by the THEMIS-1 satellite at 24 Re down the magnetotail. This sequence is often interpreted as the tailward retreat of a single reconnection site. However, another THEMIS satellite at 5 Re earthward from THEMIS-1 observed a similar earthward flow 2 min later. Thus, the observed sequence rather corresponds to a tailward leap of the reconnection site.

Each of the tailward and the earthward flows was accompanied by an auroral brightening. The first brightening was observed near the THEMIS-1 footpoint 1 min after the tailward flow. As the first brightening subsided, the second brightening occurred near the same longitude but at a higher latitude 1 min after the earthward flow was observed by THEMIS-1. Thus, the poleward leap of the brightening appears to be associated with the tailward leap of the reconnection site. The first auroral brightening subsided when a new brightening occurred. We suggest that this decay is caused by the formation of a new reconnection site which ejects northward magnetic field lines earthward and brake the previous reconnection site located in the earthward side of the new site.

多重オンセットのサブストームについて事例解析を行った。その結果、磁気リコネクションの位置が、尾部側に leap することを見いだした。本研究では、THEMIS 編隊衛星の磁気圏尾部観測と、北米・グリーンランドの地上オーロラ全天観測を用いた。全天カメラでのサブストーム開始時に、尾部側 24 Re の THEMIS-1 衛星は、プラズマ流が尾部向きから太陽向きへ 10 分程度のタイムスケールで反転することを観測した。この反転シークエンスは、しばしば、一つの磁気リコネクション領域が、尾部側に retreat していることを、衛星が観測したと解釈される。しかし、この反転よりも 2 分後に、THEMIS-1 よりも 5 Re 地球側に滞在していた THEMIS-2 衛星は、地球向き高速流を観測した。従って、この反転シークエンスは、一つのリコネクション領域の retreat ではなく、新たなリコネクション領域が遠方で生じたことを意味すると考えられる。

THEMIS-1 における、尾部向きの高速流と、地球向きの高速流に対応して、オーロラの増光が観測された。これらの増光は、THEMIS-1 衛星の footpoint と同じ経度で観測され、最初の増光よりも二番目の増光はより高緯度で観測された。従って、リコネクション領域の尾部側への leap が、オーロラの高緯度への leap に対応していると考えられる。また、最初の増光が終了すると、二番目の増光はより高緯度で観測された。この特徴は、新たに生じたリコネクションが北向きの磁力線を地球側に供給し、前に生じたリコネクションを停止させることを示唆する。

低高度衛星観測データを用いた磁気圏プラズマの乱流的領域の分布とダイナミクスの推定

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Distribution and Dynamics of Turbulent Region in the Magnetosphere Inferred from Magnetic Field Data Obtained by LEO Satellites

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Iyemori et al.(1987) showed that the small-scale magnetic fluctuations over the high-latitude ionosphere are mainly caused by the small-scale field aligned currents by using the MAGSAT data.The generation mechanism of field-aligned currents in the magnetosphere is related to the plasma motion and/or spatial gradient of plasma parameters.So they also suggested that if the small-scale fluctuation mainly come from quasi-static field aligned currents which are generated in the equatorial region of magnetosphere, the scale size and amplitude of the fluctuations will give us the information on the turbulence in the magnetospheric plasma.

In this research plan, we aim to reveal the relations between the statical distribution of plasm turbulence in the magnetosphere and their dynamics.We use the data obtained by the CHAMP and the SWARM satellites.These satellites are on near polar orbit, so that their observations can cover various LT region where MAGSAT couldn't observe.In addition, because the resolution of magnetometer of both satellites (0.065nT) is higher than that of MAGSAT (0.5nT) we can analyze the phenomena in more detail.

In this presentation, at first, we show that these small-scale magnetic fluctuations are generated by the field-aligned currents.

Next, we report the relation between the characteristics of these magnetic fluctuations (appearance location and amplitude) and the geomagnetic disturbance index, such as AE index and the Dst index.

Iyemori et al.(1987) は、MAGSAT 衛星を用いて電離層高緯度域における微小な磁場変動について、振幅の季節変化等の特徴から微小磁場変動は微細な沿磁力線電流の衛星軌道に沿った空間構造であるとした。また、電離層高度で観測される沿磁力線電流の生成機構は磁気圏のプラズマの動きやプラズマパラメータの空間的な勾配と関連があることから、仮に微小磁場変動が主に磁気圏赤道領域で生み出される準静的な沿磁力線電流に由来するものであるならば、変動のスケールや振幅は磁気圏プラズマの乱流的構造についての情報をあたえる可能性を提示した。

本研究では CHAMP 衛星および SWARM 衛星群の観測した磁場データを用いて、磁気圏内における乱流的構造の統計的分布とそのダイナミクス、すなわちサブストーム等の関係を調べる予定である。これらの衛星は MAGSAT では実現できなかった様々なローカルタイムでの観測を実現している。また CHAMP 衛星、SWARM 衛星群ともに非常に高分解能 (0.065nT) なデータを取得しているため、MAGSAT(分解能 0.5nT) では観測できなかった、より微細な変動のデータも取り扱うことが可能である。

本発表では、まず極域での磁場観測データを解析し、注目している微小な磁場変動が主に沿磁力線電流によるものであること、すなわちそれら磁場変動が沿磁力線電流の空間構造であることを示す。

その上で、それらのデータを用い磁場変動の出現位置や振幅とサブストームなどによる地磁気擾乱指数 (AE 指数や Dst 指数) との対応を昼側、夜側および北半球、南半球とで調べた結果を報告する。

また、夜側では AE 指数との非常に良い相関が見られるのに対し、昼側ではあまり相関が見られないなどの特性からサブストーム等の現象と、磁気圏内のプラズマの乱流的構造の分布との関連についても推定する。

サブストームと磁気嵐の関係

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Relation between the substorm and the storm

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Recently, almost all of the substorm signatures are reproduced in the global simulation and the dynamics of the substorm are understand quite well. The substorm is the sudden pressure enhancement in the inner plasma sheet that is caused by a change of force balance in the plasma sheet. This force balance results in the increases of tension associated with the dipolarization and balancing plasma pressure. Increase of plasma pressure is, at the same time, recognized as an injection and formation of the partial ring current. On the other hand, the ring current, which is the main signature of the storms, is a structure in which high-energy particles are trapped in the inner magnetosphere. The ring current is located further inside the part ring current. The ring current is generally regarded as the drift motion of the high-energy particles that are higher energy part of the plasma supporting the pressure. According to the increase of IMFBz negative value, the plasma responsible for the pressure is injected deeper into the inner magnetosphere, but while it is flowing into, it is flowing out not to resunt in the ring current. However, if dynamic development is reproduced by the simulation under changing IMFBz, it can be a ring current. In the fluid picture, drift motion is thermal motion, and not the fluid motion equivalent to the electric field. The drift motion is represented as magnetization current.

最近、サブストーム主要変動のほとんどがグローバルシミュレーションで再現されるようになり、サブストームの力学構造は良くわかるようになった。プラズマシートの力バランスの変更に伴い、内部磁気圏で、双極子化による張力の増加とそれにバランスするプラズマ圧力の増加が発生するのがサブストームである。プラズマ圧の増加はインジェクションとして認識されると同時に、磁化電流の発生を通じて部分環電流を形成する。一方磁気嵐の主要構造である環電流は、内部磁気圏に高エネルギー粒子が補足された状態である。環電流は部分環電流のさらに内側にある。環電流はこの高エネルギー粒子のドリフト運動として捉えるのが一般的であり、圧力を担うプラズマのさらに高エネルギー部分と連想されている。圧力を担うプラズマは IMFBz が負に大きくなるにしたがって、より内部の磁気圏に流入するが、IMFBz が一定なら流入する一方で流出し、環電流とはならない。しかしながら IMFBz が変動する状況をシミュレーションで再現すれば、環電流となりうることが分かる。流体的な描像では、ドリフト運動は熱運動であり、電場と等価な流体運動ではないので、磁化電流として扱われる。

土星磁気圏界面での磁気リコネクション

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Magnetic reconnection at Saturn’s magnetopause

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Magnetic reconnection is an important process that occurs at the magnetopause boundary of Earth’s magnetosphere because it leads to transport of solar wind energy into the system, driving magnetospheric dynamics. However, the nature of magnetopause reconnection in the case of Saturn’s magnetosphere is unclear, and has been the subject of debate. Here we review this topic, and assess when and where reconnection is likely to occur on the Saturnian magnetopause. We discuss the influence of bulk flow shears and local plasma beta conditions on magnetopause reconnection onset, including their anticipated effect on the reconnection rate. Both these factors are expected to have a negative influence on the reconnection process at Saturn’s magnetopause, compared to reconnection at Earth’s magnetopause. Studies to date imply that the nature of solar wind-magnetosphere coupling via reconnection can vary between planets, and we should not assume that the nature of this coupling is always Earth-like.

極方向に伝搬するカスプオーロラの動的特性: 全天イメージャ観測に基づく統計解析

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Dynamical characteristics of poleward moving auroral forms: A statistical analysis with all-sky imager observations

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We have developed an algorithm for automated detection of poleward moving auroral forms (PMAF) from successive 630.0 nm all-sky images obtained in the dayside cusp region. The algorithm simply extacts a line of zero intensity in differential all-sky images as a trace of PMAF. By tracking the motion of such zero lines we are able to follow the trajectory of the poleward propagation of PMAFs and estimate their moving velocity. We applied the algorithm to 3-season observations of all-sky airglow imager in Longyearbyen, Norway. As a result, we succeeded in extracting a number of PMAFs and have studied their dynamical characteristics (speed and direction of propagation, lifetime etc.). By comparing the derived statistical characteristics of PMAF with the background ionospheric convection from SuperDARN, we discuss the motion of PMAF in terms of the interaction between the solar wind and the dayside magnetosphere.

昼間側電離圏カスプ域では，惑星間空間磁場が南向きの時に，極方向へオーロラが準周期的に移動する現象，いわゆる Poleward Moving Auroral Form (PMAF) が頻繁に観測される．PMAF は，昼間側磁気圏界面で磁気リコネクションによって間欠的に引き起される磁束の移動現象である Flux Transfer Event (FTE) の電離圏への投影であると考えられている．過去の研究において，PMAF の特性は，地上光学観測を用いて調べられてきた．Fasel [1995] は，Meridian Scanning Photometer のデータから大量の PMAF を抽出し，その動きが 3 つのタイプに大別されることを示した．しかし，Fasel [1995] では，PMAF の抽出が目視で行われているために PMAF の同定に関して明確な基準がなく，3 つのタイプに客観的な違いを見出しづらいという難点があった．本研究は，ノルウェー北部ロングイヤービエンに設置されている全天カメラのデータから PMAF を自動的に，かつ客観的に検出するアルゴリズムを開発し，その手法を 3 シーズンの観測データに適用することによって PMAF の動的な特性を明らかにする事を目的としている．

新しく開発した手法では，まず始めに PMAF の動きを追跡するために，約 10 秒毎に得られた 630.0 nm 全天画像間の時間差分画像を作成する．PMAF は極方向に移動する為，差分画像においては北側に輝度値の増加領域，南側に減少領域が現れることになる．差分画像の中から，北側に輝度値の増加領域を，南側に減少領域を持つ構造を抽出する事で，PMAF を検出することが可能になる．また，抽出した PMAF を追跡することで，伝搬速度などの動的な特性を推定することもできる．本研究では，このアルゴリズムを用いて 3 シーズンのデータから 50 例以上の PMAF を検出することで，その動的な特性を統計的に調べた．発表では，PMAF の伝搬速度や移動方向を決定している要因について，SuperDARN によって得られた背景対流との比較を踏まえて考察を行った結果を報告する．

複数の観測機器を用いたSun-Aligned Arc上空のプラズマ粒子環境の観測

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Multi-instrument observations of multiple sun-aligned arcs

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Sun-aligned arcs (SAA) are one of the outstanding phenomena at the highest part of the polar ionosphere during prolonged periods of northward interplanetary magnetic field (IMF). Particle signature of SAA has been studied for a long time by using low Earth orbiting spacecraft. Many of the past studies showed an existence of field-aligned potential drop above SAA. Although a number of studies have been conducted at low altitude, there has been almost no studies which combines auroral image together with high and low altitude particle observations. For this reason, very little has been known about the field-aligned transport of electrons and ions above SAA.

In this paper, we aim at combining in-situ plasma measurements by Cluster at the top of the acceleration region and DMSP at low-altitude together with optical observations of SAA from an all-sky imager (ASI) at Resolute Bay, Canada (74.7 N, 265.0 E, 82.9 MLAT). During a 4 h interval on November 10, 2005, a series of SAA was observed by the ASI at Resolute Bay. In the central part of the present interval, the ionospheric footprints of the 4 Cluster satellites encountered the SAA sequentially and observed well correlated enhancements of electron fluxes at weak energies (< 1 keV). The Cluster satellites also detected signatures of upflowing beams of ions and electrons in the vicinity of the SAA. This implies that these ions and electrons were accelerated upward by a quasi-stationary electric field existing in the vicinity of the SAA. In this presentation, by combining data from multiple instruments, we discuss the fundamental characteristics of field-aligned plasma transport associated with optical signatures of SAA.

Sun-Aligned Arc (SAA) はオーロラ帯より高緯度で見られるオーロラの1つである。SAAの上空には、磁気圏からオーロラ電子が降下しているが、それらの電子は、加速域に存在する磁力線に平行な方向の電場によって加速されていると考えられている。この上向きの加速電場は、同時に電離圏のイオンを磁気圏へと運びだすと予想される。このようなSAA上空のプラズマ環境について、これまで低軌道衛星による研究が行われており、SAA上空には磁力線に沿ったポテンシャルドロップが存在することが示唆されてきた。しかし、これまでの多くの粒子観測が低高度で行われてきたため、高高度と低高度の衛星観測と、地上光学観測を組み合わせた研究はほとんど行われてこなかった。このため、SAA上空の磁力線に沿った電子とイオンのダイナミクスについて未だに詳細な理解は得られていない。

本研究では、加速域より高高度を飛翔するCluster衛星と低高度を飛翔するDMSP衛星、またカナダ・レゾリュートベイに設置されている全天大気光イメージャによるSAAの同時観測事例について解析を行った。2005年11月10日0030 - 0430 UTに全天イメージャによって、複数のSAAが観測された。この時間帯において4機のCluster衛星の電離圏フットプリントはSAAを横切り、そのタイミングで1 keV以下の弱いエネルギーを持つ降下電子フラックスの増大を検出した。また、Cluster衛星は同じタイミングで上向きのイオンのフローと、その時間帯の前後に、SAA近傍において上向きの電子ビームを検出した。これらの観測結果は、SAA上空において、電離圏起源のイオンと電子が準静電的な電場によって上向きに加速されている事を示している。発表では、複数の観測機器のデータを組み合わせた解析により明らかになった、SAA上空の磁力線に沿ったプラズマ輸送過程と地上光学観測結果との関連性について考察を行う予定である。

ベイズ推定に基づくVLF波動の伝搬ベクトル推定に関する研究

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Study on direction finding method based on Bayesian inference

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Investigating characteristics of plasma waves observed by scientific satellites in the Earth's magnetosphere is the effective key to understand not only generation mechanisms of the waves but also a plasma environment which influences its generation and propagation conditions. In particular, direction finding of the waves is important for understanding the propagation characteristics of VLF waves. In order to find the directions, the wave distribution function (WDF) method was proposed[1, 2]. This method is derived from the concept that observed signals consist of a number of elementary plane waves and can be defined as wave energy density distribution. However, solving its equations is a so-called ill-posed problem and the solution is not determined uniquely, hence we must assume an adequate model as a solution. Although many models have been proposed until now[3, 4], we have to select the most optimum model depending on situations because each of the models has disadvantages as well as advantages. In the present study, we developed a new method for direction finding of the plasma waves measured by plasma wave receivers to solve problems of conventional methods. This method is based on Bayesian inference and its model parameters assume stochastic parameters.

Using computer-generated test data, we evaluated our proposed method, and compared with two conventional methods(MEM, PTM). Moreover, we studied the problem which may arise when applying the WDF method to real observed data. As a result, in the case of the noiseless data, our proposed method is almost correctly estimated not only the directions of the peaks but also the shapes of the WDF.

As a next step, we developed a new spectral analysis method based on compressed sensing[5]. This method assumes that data can be represented as sparse in frequency domain. As a result of numerical experiments, the method is very effective compared with a FFT using a window function, and it was shown that the method has both high frequency resolution and wide dynamic range. This method is applicable for data compression onboard a satellite and information extraction of observed data.

地球磁気圏内の科学衛星で観測されるプラズマ波動の特性の調査は, 波動の伝搬機構だけでなく, 励起・伝搬条件に影響を与えるプラズマ環境を理解するための重要な要素である. 特に, VLF 波動の伝搬特性の把握のためには波動の伝搬方向が重要となり, 伝搬方向の推定のために波動分布関数法が提案されている [1, 2]. この手法は観測される信号が複数の平面波から構成されているとみなし, それをエネルギー密度分布として表現する. しかし, この手法の求解は不良設定問題であるため解が一意に定まらず, 解として適切なモデルを仮定する必要があった. これまでに多くのモデルが提案されてきたが [3, 4], どのモデルも一長一短であるため解析対象に応じて適切なモデルを選択する必要があった. そこで, 本研究では従来手法の問題点を克服するためにプラズマ波動観測器によって観測されるプラズマ波動の伝搬ベクトル推定手法を新たに開発した. 本手法はベイズ推定に基づくものであり, そのモデルパラメータは確率変数として扱われる.

疑似データを用いて, 提案手法の評価を行い, 従来手法と比較を行った. 更に, 実観測データを波動分布関数法に適用した場合に起こりうる問題について評価・検討を行った. 数値実験の結果, ノイズを含まない場合に提案手法が波源の到来方向だけでなく波源の広がりを含め良好な推定を行えることが分かった.

次に, 我々は圧縮センシング [5] に基づく新たなスペクトル解析手法を開発した. 本手法はデータが周波数領域においてスパースな表現が可能であることを仮定している. 数値実験より, 本手法が窓関数を用いる高速フーリエ変換に比べて非常に有用であり, また高い周波数分解能と広いダイナミックレンジを有していることが示された. またこの手法は衛星機上でのデータの圧縮処理や観測データからの情報抽出に応用が可能である.

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あけぼのVLF/WBAで観測された雷ホイスラの統計解析、及び電子密度分布推定へ向けたその利用法の検討

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Statistical analyses of lightning whistlers observed by VLF/WBA onboard AKEBONO and their prospect for application study

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Lightning whistler is a very low frequency electromagnetic wave originating from lightning discharge. Although most of energy from lightning discharge travels among Earth-ionosphere waveguide, a fraction of the energy passes through the ionosphere and propagates approximately along a geomagnetic field line to the opposite hemisphere. Dispersive spectrum is a well-known characteristic of lightning whistler. Their dispersion depends on the electron density profile and the gyrofrequency along the propagation path, and the path length. Since earlier studies, lightning whistlers were frequently observed by both ground and satellite based instruments. They have been investigated in connection with various phenomena in the plasmasphere such as loss processes of electrons in the Van Allen radiation belts. Therefore, comprehensive understanding of characteristics of lightning whistler as a function of latitude and longitude, local time, season, and solar activity using long-period observation data enables us to evaluate how much effect is given by the whistlers on these phenomena.

In the current study, we statistically analyzed lightning whistlers in the long-period data obtained by the VLF/WBA onboard the AKEBONO spacecraft. Some statistics such as spatial distribution, local time and seasonal variations of the occurrence frequency were already performed using the 22 years data from 1989 to 2010 tracked by the USC (Uchinoura space center) station in Japan. In addition, the same statistics have been derived from the 8 years data from 1999 to 2007 tracked by the ESR (Esrange space center) station in Sweden. These statistical analyses show the similar results except that lightning whistlers in the ESR data frequently occur in higher latitude region compared with those in the USC data. The detailed reason of this difference is now under study.

In this presentation, we report the statistical results derived from the USC and ESR data so far. We also discuss the estimation method of electron density profile using the dispersion trend of lightning whistlers in the WBA data.

雷ホイスラは雷放電を起源とするVLF波動である。雷放電から発生したエネルギーの大部分は地球と電離層間を導波管伝搬するが、そのエネルギーの一部は電離層を通過し、地磁気の磁力線に沿って反対半球まで伝搬する。雷ホイスラの主な特徴として分散性が挙げられ、その度合いは伝搬経路上の電子密度分布、背景磁場強度、そして伝搬距離に依存するということがよく知られている。これまでに、地上及び衛星観測で多数の雷ホイスラが確認され、それらホイスラとプラズマ圏での波動や粒子との関連性が議論されてきた。これら物理現象への雷ホイスラの影響度を適切に評価するためには、長期観測データを利用しての緯度経度やローカルタイム、季節等に対する雷ホイスラの空間・時間的な特性の包括的な理解が必要となる。

本研究では、あけぼの衛星搭載のVLF/WBAの長期観測データを用いて、雷ホイスラの統計解析を行った。これまでに、内之浦スペースセンター(USC)で1989年から2010年までに追跡した22年分のデータを用いて、ホイスラ発生頻度の空間分布、及びローカルタイム・季節依存性といった統計結果が得られているが、今回はそれに加え、エスレンジスペースセンター(ESR)で1999年から2007年までに得られた8年分のデータに対して、同様の統計解析を行った。USCとESRから得られた統計結果は、概して似た傾向を示したが、空間分布については、ESRで観測されているホイスラのほうが高緯度領域で発生しやすいという差異が見られた。この原因については現在調査中である。

本発表においては、USC, ESRそれぞれのデータから得られた雷ホイスラ発生頻度の統計結果の報告、及びその類似点や差異について議論を行う。また、統計データの応用として、あけぼのの軌道周回に沿ったホイスラの分散傾向から、電子密度分布を推定する手法についての検討を述べる。

GEMSIS-RC,RB コードに基づく単波長 Pc5 波動による放射線帯電子のドリフト共鳴の効率について

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Efficiency of drift resonance of outer radiation belt electrons with monochromatic Pc5 waves based on GEMSIS-RC and RB simulations

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Radial transport of relativistic electrons due to Ultra Low Frequency (ULF) waves in the Pc5 frequency range is one of important candidates of the acceleration and loss processes of the outer radiation belt electrons. The drift resonance with global Pc5, in which interaction between the electron drift motion in the dipole-dominated magnetic field configuration and the electric and magnetic fluctuations of Pc5 waves induce the radial transport, has been considered as a driver of radial diffusion of relativistic electrons across the drift shells. On one hand, the Pc5 amplitude decreases rapidly with decreasing radial distance, and the recent studies has pointed out that the efficiency of radial transport caused by the Pc5 waves can be highly depending on the characteristics of the waves [e.g., Ukhorskiy and Sitnov, 2008]. The result indicates that collective motion of the outer belt electrons can exhibit large deviations from radial diffusion. Thus it is important to understand the fundamental behavior of collective motion of the electrons against the Pc5 waves in the inner magnetosphere.

In this study, we combine two simulation models of the inner magnetosphere: GEMSIS-RC (ring current) and RB (radiation belt) models. The GEMSIS-RC model is a self-consistent and kinetic numerical simulation code solving the five-dimensional collisionless drift-kinetic equation for the ring-current ions in the inner-magnetosphere coupled with Maxwell equations [Amano et al., 2011]. The GEMSIS-RB code conducts test particle trajectory tracings of relativistic electrons in arbitrary magnetic and electric field configurations [Saito et al.,2010]. We first conduct Pc5 wave simulation with GEMSIS-RC, and then the obtained time variations of the magnetic and electric fields are used as an input to GEMSIS-RB code to understand the transport of relativistic electrons due to the Pc5 waves. For simplicity, we investigated the effects of monochromatic wave on the radial transport of electrons, i.e., the dependence on such parameters as energy, pitch angle, and initial location of the electrons.

Pc5 周波数帯範囲の超低周波（ULF）波動による相対論的電子の動径方向輸送は、放射線帯電子の加速と損失のプロセスの重要な候補の一つである。双極子磁場における電子のドリフト運動と Pc5 波動との相互作用によるドリフト共鳴は、相対論的電子のドリフト軌道からの動径方向拡散を担っていると考えられている。一方で、Pc5 波動の振幅はドリフト軌道の半径が小さくなるにつれて急速に減少していることから、最近の研究では、動径拡散効率は Pc5 波動の依存性が高い可能性があると指摘されている [Ukhorskiy and Sitnov,2008]。その結果、放射線帯外帯電子の集団的運動は、動径方向に大きく変化することを示している。したがって、内部磁気圏における Pc5 波動に対する電子の集団的運動の基本的なふるまいを理解することは重要である。

本研究では、GEMSIS-RC（リングカレント）と RB（放射線帯）モデルという内部磁気圏の 2 つのシミュレーションモデルを組み合わせている。GEMSIS-RC モデルは、マクスウェル方程式を組み込んだ、内部磁気圏のリングカレントイオンにおける 5 次元無衝突ドリフトの運動方程式を解く数値シミュレーションコードである [Amano et al. 2011]。GEMSIS-RB コードは、任意の電磁場で相対論的電子の試験粒子の軌道追跡を行うコードである [Saito et al. 2010]。最初に GEMSIS-RC を用いた Pc5 波動のシミュレーションを実行し、その後、得られた電磁場の時間変動に起因した Pc5 波動に対する相対論的電子の輸送を理解するため GEMSIS-RB コードへ入力する。まず、電子の動径方向の輸送に帯する単色波の影響、すなわち粒子のエネルギー、ピッチ角、及び電子の初期位置のようなパラメータの依存性を考察する。

衛星搭載波形観測機用デジタル信号処理FPGAモジュールの評価用ボードの開発

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Development of the FPGA board for evaluation of onboard digital signal processing of plasma wave

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In recent years, a lot of satellites are launched to measure space environment as a consequence of plasma dynamics controlled by solar activity. Measuring plasma wave is one of important clues to understand plasma physics around the earth, and it is necessary to implement intelligent signal data processing techniques into the plasma wave instruments. In the conventional wave instruments, these data processes are executed by a CPU, and thus the computation speed is not fast enough to enable real-time processing. It is necessary to reduce the weight and size of the instruments to meet the requirements of flying formation satellites and planetary exploration spacecraft. Recently, FPGA is often used to solve these problems. In such a background, we develop a FPGA board, which enables us to develop arbitrary digital signal processing applicable for the future missions. The developed FPGA board is designed to evaluate the performance of the developed module easily. In the presentation we will introduce the FPGA board as well as the current status of our development of digital signal processing modules especially for the real-time signal processing technique.

地球磁気圏をはじめ，太陽系内惑星近傍のプラズマ環境探査の目的で，数多くの科学衛星が打ちあげられている．プラズマ波動観測は，観測領域のプラズマ電磁環境を知るうえで重要な観測手段であるが，一般にプラズマ波動の生波形観測は，地上に送信可能なデータ量に対して膨大であるため，取得した波形データに対して，機上で数多くのデジタル信号処理を必要とする．従来，これらの多くはCPUを使ったソフトウエアによって処理されているが，搭載可能なCPUのリソースの制約から，リアルタイム処理が困難である．また今後，地球磁気圏内の複数衛星による編隊観測や，惑星探査用の搭載機の開発を考えると，観測器のさらなる小型・軽量化が必須である．この問題に対し，近年，FPGAを使用することでデジタル信号処理の高速化と観測装置の小型化が図られている．このような背景のもと，我々は，衛星機上におけるデジタル信号処理のFPGA化のための開発を効率化するために，汎用的に利用可能なFPGAボードを開発し，今後開発を目指す各種のデジタル信号処理の動作を評価できる環境整備を進めている．本稿では，評価に用いるFPGAボードの概要を紹介するとともに，それを使った信号処理モジュールの検証および評価について述べる．本研究では，サブバンド圧縮処理を評価の対象とし，リアルタイム処理可能なモジュールを構成した．

評価に使用するFPGAボードは，電磁界各3成分，計6成分の信号入力を想定し，それらの信号処理結果を容易に確認・評価できることを目的としている．この目的のために，同評価ボードは，入力された6系統の信号を保管・処理を行うためのモジュール(Mod#1)に加え，任意の信号を6系統同時に出力できるモジュール(Mod#2)を備える．各モジュール共に，FPGA(Cyclone iv)とDDR2メモリ(128MByte)が各1個ずつ搭載されている．またMod#2からの出力信号をMod#1に入力するための仕組みとして，Mod#2にはDAC(Digital Analog Converter)が6系統，Mod#1にはADC(Analog Digital Converter)が6系統搭載されているほか，両モジュール間で直接デジタルデータを流すラインも設けられている．また，両モジュールにつながるCPUが1つ搭載されており，TeraTermを通じてMod#2上のDDR2(MEM#2)への任意波形の書き込みや，双方のモジュールのDDR2(MEM#1,MEM#2)内のデータ読み出しが可能となっている．これらの機構を通じて，評価者は任意の波形をMod#2側から送出し，処理後のデータをMod#1側から読み出して確認することが可能である．

現時点では，Mod#2・Mod#1間でデジタルデータを直接受け渡して開発を進めているが，将来的にはADCおよびDACを用いてアナログ信号の入出力機能も用いたテストも行うことを想定している．現在，最も喫緊の課題のひとつに，観測波形のリアルタイムでの圧縮処理があり，今後，同評価システムを利用して，サブバンド圧縮モジュールの動作検証および評価を行う．

地球磁気圏境界付近で観測された磁気圏静穏時における粒子のインジェクション

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Particle injections observed near Earth’s magnetopause in quiet conditions

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Particle injection is sudden enhancement in flux of energetic charged particles, commonly observed at geosynchronous orbit (6.6R_E), and associated with magnetospheric substorms. Since 2007, dispersive particle injections have been observed in the further dawnside of the Earth’s magnetosphere (8~14R_E) than geosynchronous orbit in quiet conditions with the spacecraft Geotail and THEMIS. Although only electron injections are observed in 22 cases, both electron and ion injections are observed in 18 cases. The injected population displays energy dispersion in which more energetic particles arrive at a given location earlier than less energetic particles. The time delay is from 15 to 90 minutes between 10 keV electrons and 40 keV. In the case in which both electron and ion fluxes increase, the enhancement of electron flux starts earlier than that of ion flux. In order to investigate the time delay, we have calculated particle trajectories in the inner magnetosphere. We use the Tsyganenko model which is an empirical magnetic field model of magnetosphere. We assume that the magnetospheric electric field is sum of a convection electric field and a corotation electric field, and obtain the particle trajectories in the equatorial plane using particle drift velocity. The simulations show that electrons drift from the nightside through the dawnside to the dayside while ions drift from the nightside through the duskside to dayside. However, in most cases, ions do not arrive in the observed region and exit magnetosphere. In this study, we investigate ion trajectory in more detail and conditions in which those injections occur with multi-satellite observations and IMF data.

２００７年ごろから磁気圏静穏時に地球半径の８～１４倍程度の朝側から昼側にかけた領域で、数 keV - 数十 keV の粒子のフラックスが増加するインジェクションが人工衛星 Geotail や THEMIS で観測されている。２００７年から２０１３年の間に、電子のインジェクションが４０例ほど観測され、このうち半数近くの１８例では、イオンのインジェクションも同時に観測されている。また、これまでにサブストームが起こっているときに静止軌道で観測されてきたインジェクションとは違い、磁気圏では大きな磁場の変動はなく静穏な状態のときに観測されている。観測された荷電粒子のフラックスは方位角方向に等方的であり、粒子がどのようにドリフトしてきたかは明らかではない。このインジェクションはエネルギー分散を伴っており、粒子のエネルギーごとのフラックスの時間変化を見ると、エネルギーが高い粒子の方がエネルギーが低い粒子よりも早くフラックスが増加し始めていることがわかり、１０ keV の電子と４０ keV の粒子のフラックスが増加し始める時刻の差は、１５分～９０分であった。また、電子フラックスの増加時刻と、イオンフラックスの増加時刻にも時間差があり、電子よりもイオンの方が、遅れて増加する。これらの注入されてきた粒子の軌道とエネルギー分散について調べるため、磁気圏の磁場を Tsyganenko モデルを用い、電場を一様電場と共回転電場の足し合わせとして、赤道平面で荷電粒子の軌道を計算した。その結果、電子は、尾部から朝側方向へドリフト運動し、観測された朝側～昼側の領域に到達する軌道をとった。電子のエネルギー分散に関しても観測とおよそコンシステントな結果を得た。しかし、イオンは、多くの場合、観測領域に到達するまでに磁気圏境界から出てしまう軌道をとった。そのため、このインジェクションが起こる条件を解明するためには、イオンが観測領域に到達する条件を観測とシミュレーションによってより詳しく調べる必要があることがわかった。Geotail 衛星と THEMIS 衛星での粒子フラックス増加の観測と、地上の磁場や惑星空間磁場の変化等から、このようなインジェクションが起こる条件について詳しく調べる。

Daily variation of geomagnetic field Z component during geomagnetic storm

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It is well known that the geomagnetic field disturbances during storm time observed on the ground, especially north-south (H) component of the field is produced by the ring current around the earth's equator. The D component of the field is also disturbed by the asymmetric distribution of current system during storm time PRC (Partial Ring Current). However there is few report how the global distribution of Z component response during storm time.

By using the geomagnetic field data obtained from MAGDAS/CPMN network [K.Yumoto et al., 2006 and 2007], we investigated the Z-component distributions during storm-time, and found that there is almost no difference between the Z components of Sq in the quiet time and the storm time at the observatories located in inland area like Kuju observatory. It is well known that the horizontal component, especially H component, of Sq disappear during the storm time as we mentioned above but it is possible that there is no relationship between the intensity of the Sq current and the geomagnetic storm according to the result of the Sq Z component indifferent to the storm.

On the other hand, there is disturbance on the Z component at some observatories during the main phase of the storm, for example the observatories near the coast or located in island, which indicates that these disturbances on the Z component is caused by GIC effect so-called the coast effect [Parkinson, 1959; Parkinson and Jones, 1979]. It is consistent with the feature of ground-induced current, which the vertical component is enhanced by the geomagnetic field whose high frequency change near the coast, as reported by Mason, [1962]; Greenhouse, [1972], etc. that the disturbance on the Z component of the geomagnetic field near the coast area can be observed during only the main phase of the geomagnetic storm.

Geotailの長期観測電子データの見積もりに基づいたプラズマシートの太陽風依存性の研究

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Investigation of solar wind dependence of the plasma sheet based on long-term GEOTAIL/LEP electron data evaluation

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It is observationally known that the plasma density and temperature in plasma sheet are significantly changed by solar wind conditions [e.g., Terasawa et al., 1997]. Thus it is considered that the plasma sheet plasma is originated from the solar wind, and several entry mechanisms have been suggested. When the interplanetary magnetic field (IMF) is southward, the solar wind plasma enters the plasma sheet mainly through magnetic reconnection at the dayside magnetopause. In contrast, for the northward IMF, the double-lobe reconnection [Song et al., 1999], abnormal diffusion [Johnson and Cheng., 1997], and plasma mixing through the Kelvin-Helmholtz instability caused by viscous interaction [Hasegawa et al., 2004] have been proposed. Relative contribution of each process is, however, far from understood.

In the present study, we use magnetotail observations by the Geotail spacecraft at radial distances of 10-32 Re during 12-year period from 1995 to 2006 to investigate properties of the plasma sheet. We conducted a statistical analysis with calibrated LEP-EA [Mukai et al., 1994] ion and electron data. We selected central plasma sheet observations and derived electron and ion temperature and density using the same method and criteria as Terasawa et al. [1997]. In addition, OMNI solar-wind data are used. The results show that the plasma sheet density (both ion and electron temperatures) has a good correlation with the solar wind density (kinetic energy) over the whole solar cycle. We find clear dawn-dusk asymmetry in the temperature ratio Ti/Te, i.e., the average Ti/Te is higher on the duskside than the dawn. The density also shows the dawn-dusk asymmetry and higher on the duskside than on the dawnside. A previous study by Wang et al. [2012] showed that Ti/Te is high (typically 5-10) in the magnetosheath. The statistical results, therefore, suggest that the shocked solar wind plasma can easily enter the duskside plasma sheet rather than the dawnside. We will discuss the possible mechanisms of the entry of the cold plasma into the duskside plasma sheet.

プラズマシートの温度や密度は太陽風の状態によって明らかに変化することが観測的に知られている [e.g., Terasawa et al., 1997]。このことより、プラズマシートのプラズマは太陽風が起源であると考えられており、いくつかの侵入経路が提唱されている。惑星間空間磁場（IMF）が南向きのとき、太陽風プラズマは主に昼側磁気圏界面での磁気リコネクションを通して侵入する。それに対し、北向き IMF 時はダブルローブリコネクション [Song et al., 1999]、異常拡散 [Johnson and Cheng., 1997]、粘性相互作用によるケルビン－ヘルムホルツ不安定性を通した混合 [Hasegawa et al., 2004] が提唱されている。しかし、それぞれの経路の相対的な寄与はわかっていない。

この研究では、プラズマシートの特性を調べるために 1995 年から 2006 年の 12 年間に亘る半径方向 10 － 32Re の Geotail 衛星による磁気圏尾部観測を用いる。較正した LEP － EA[Mukai et al., 1994] のイオンと電子データを統計解析した。我々は Terasawa et al. [1997] と同じ方法と基準で中央プラズマシートの観測を選択し、温度と密度を見積もった。それに加え、OMNI 太陽風観測データも使用した。その結果、太陽活動周期を通じてプラズマシートのプラズマシートの密度（イオンと電子の温度）は太陽風の密度（運動エネルギー）とよい相関があることがわかった。我々はプラズマシートのイオンと電子の温度比 Ti/Te に明らかな朝－夕非対称があること、つまり、平均した Ti/Te は朝側よりも夕側の方が高かった。密度にも非対称性があり、朝側よりの夕側の方が高かった。Wang et al. [2012] の先行研究より、磁気シースの Ti/Te は高い（典型的に 5 から 10）ことが示されている。そこで、統計解析結果より、衝撃波を通過した太陽風は朝側より夕側で簡単にプラズマシートに侵入することを提唱する。夕側プラズマシートで冷たいプラズマが侵入する機構の可能性について議論する。

シータオーロラ形成時における磁気圏構造とプラズマ対流：次世代M-I結合系シミュレーションコードによるMHDモデリング

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Magnetospheric structure and plasma convection associated with theta auroras: A next-generation MHD simulation

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A theta aurora is an optical phenomenon that consists of an 'auroral oval' (a luminous ring) and a 'transpolar arc (TPA)' that extends across the polar cap. Previous studies show that a theta aurora is formed when the IMF By sign changes during a prolonged northward IMF Bz period. In response to the IMF By change, a TPA starts from the dawnside or duskside aurora oval and moves toward the opposite side across the polar cap. Also, the characteristic of precipitating particles associated with the TPA is similar to that of the plasma sheet, indicating that the TPA is located on closed field lines. In spite of the vast efforts in the past, however, it is not yet understood how such an anomalous configuration is formed, how the magnetospheric structure reconfigures, and how field-aligned currents (FACs) and plasma convection evolve in the ionosphere and in the magnetosphere. The purpose of our study is to clarify such magnetosphere-ionosphere coupling processes during theta aurora formation using MHD simulation.

Previously, we calculated the simplest case in which IMF By exhibited a stepwise change during a northward IMF period, using the MHD simulation code developed by one of the authors (T. Tanaka). The results showed a plasma sheet protrusion (a closed field line region) that connected to the dayside auroral oval across the entire polar cap. It was the first simulation that reproduced a perfect theta aurora configuration. In this presentation, we show the analysis results of the simulation, in particular, the reconfiguration of the magnetospheric null-separator structure during the theta aurora formation.

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シータオーロラとは、環状に現れる通常の発光領域' オーロラオーバル' と、極域を横断する発光領域' トランスポーラーアーク (TPA)' からなる発光現象のことである。過去の研究から、シータオーロラは IMF が北向きの間に IMF By の符号が変化すると形成される、ということがよく知られている。TPA は朝側・夕方側どちらかのオーロラオーバルからはがれるようにして発生し、極域を横断するように反対側へ動くということが観測により確認されている。また、TPA 領域の降下粒子の特徴がプラズマシートのものと似ているということなども観測から明らかになっている。しかし、どのようにしてこのような特異な形になるのかという物理的なメカニズムや、このときの磁気圏構造、沿磁力線電流のパターンなど総合的な様相はいまだに解明されていない。本研究の目的は、MHD シミュレーションでシータオーロラを再現し、そのときの磁気圏構造や電離圏プラズマ対流などを調べて、シータオーロラ形成時の磁気圏-電離圏結合系を解明することである。

著者の一人 (田中高史) が新しく開発した MHD シミュレーションコードを用いて、IMF 北向きのまま IMF By が矩形的に変化する最も簡単な場合の計算を行ったところ、昼側オーロラオーバルにつながるプラズマシート (閉磁力線領域) を再現できた。このような完全に極冠を横断する TPA を再現したのは我々が初めてである。本講演では、このシータオーロラのシミュレーションとその解析結果を紹介する。特に、磁気圏の null-separator 構造がどのように変化するかに注目して論じる。

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地上-衛星同時観測による大規模擾乱に伴う電場の発達・伝搬過程

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Evolution and propagation of electric fields during magnetospheric disturbances based on ground-based and spacecraft observations

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Magnetospheric disturbances triggered by the input from the solar wind lead to the variation of the particle and electromagnetic field. Among these processes, there is evolution of convection electric fields, which involve energy transmission from the solar wind and development of large-scale convection and current systems. It is believed that Poynting fluxes associated with the onset of convection electric fields provides a key to understand the energy transmission [*Nishimura et al.*, 2010]. However, the interaction between magnetosphere and ionosphere, such as the electric field propagation and energy transport process in the magnetosphere-ionosphere (M-I) coupled system, is still an open issue. Motivated by this issue, we focused on sudden commencements (SCs) known as one of the distinct magnetospheric disturbance phenomena triggered by the compression of the magnetosphere due to solar wind disturbances, and investigated the evolution and propagation of electric fields during SCs using in-situ electric field data by THEMIS and Van Allen Probes. We also identified the transport process of the electromagnetic energy by multi-spacecraft, SuperDARN radar, and ground magnetometer data coordinated in a wide region of the M-I coupled system. In order to judge whether SCs occurred or not, we referred the SYM-H index provided by OMNI database and low-latitude geomagnetic field (KNY). Event criteria were set as follows; (1) Low-latitude magnetometer (KNY) locates at 0-7 h UT, (2) The amplitude of SYM-H is more than 10 nT, and (3) The rise time of SYM-H is less than 5 min.

We found 21 SC events in 2013 under these conditions, and all events showed enhancements of the dusk-dawn electric field associated with SCs detected by both THEMIS and Van Allen Probes. There is little time difference between in-situ electric and magnetic field (within 5 sec), which is consistent with fast mode waves propagating across the magnetosphere. We also found that the in-situ electric field detected by THEMIS corresponds to that by Van Allen Probes, but these SC onset and peak time varied with their configuration. Moreover, the ionospheric electric field associated with SCs detected by radar observations was seen corresponding to the magnetospheric electric field.

Now we are trying to evaluate the time lag of SC onset time and peak time between the magnetospheric and ionospheric electric fields, and estimate Poynting fluxes from in-situ electromagnetic field data. These validations could verify the energy transport channel from dayside magnetosphere toward nightside magnetosphere via ionosphere that was suggested by model estimation and the single point observation.

磁気嵐時におけるプラズマシート電子内側境界の統計解析

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Statistical study of the inner boundary of the plasma sheet electrons during magnetic storms

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The locations of inner boundary of the plasma sheet electrons during magnetic storm have been analyzed statistically by using THEMIS data. Plasma sheet electrons are carried to the earth due to magnetospheric convection, and then drift toward the morning sector in the vicinity of the earth. Thus, the inner boundary of the plasma sheet electrons are formed around 3 - 7 Re. In addition, plasma sheet electrons can precipitate along a magnetic field line, and produce aurora in the earth's ionosphere.

Previous studies investigated the dependence of the location of the inner boundary of the plasma sheet electrons on geomagnetic indices such as Kp and AE index [Korth et al., 1999; Jiang et al., 2011]. Jiang et al. [2011] reported the local time distribution of the inner boundary of the plasma sheet electrons in both quiet and disturbed conditions by referring AE index. In this study, we focus not only on dependences on Dst index but also on dependences on phase of magnetic storms. The data which we used are obtained by ESA (Electrostatic Analyzer) onboard the THEMIS satellite. ESA measures the energy flux, density and temperature of particles over the energy range from a few eV to 30 keV for electrons and to 25 keV for ions. In the present study, we use ESA data of 1 to 10 keV electrons. We perform event analyses for two magnetic storms of July 6, 2013 and June 17, 2012 and a statistical analysis of the positions of inner boundary of the plasma sheet electrons.

As a result of the event analyses, the inner boundaries were located around 3 - 4 Re and 4 - 10 Re in the main phase and the recovery phase of the magnetic storm, respectively. We find that the boundaries are closer to the earth in the main phase than those identified during the recovery phase of the same magnetic storm. In addition, we find in the main phase of the magnetic storm that the identified inner boundaries are located around the similar radial distance over the analyzed energy range of the plasma sheet electrons, but in the recovery phase of the magnetic storm, we find that the inner edge of the low energy electron is closer to the earth than that of the high energy electron. In the magnetic storm of June 17, 2012, the recovery phase lasted two days, and the inner boundary in the recovery phase of the second day was further away from the earth, and the energy dependence of the location of the inner boundary becomes evident more in the second day.

Based on the results of the event analyses, we study the location of the storm-time inner boundary statistically. Frank [1971] reported that the inner boundary of low-energy plasma sheet electrons were located closer to the earth than those of high-energy plasma sheet electrons. The result of our statistical study shows the similar energy dependences in the recovery phase of small magnetic storms but different tendency in the main phase of the magnetic storm and in the recovery phase of large magnetic storms. We also reveal that the typical radial distance of the inner boundary during the storm main phase is 3.9 Re. Disappearance of the energy dependence of the location of the plasma sheet electrons suggests the presence of the strong electric field in the vicinity of the earth. Based on the location of the storm-time inner boundary revealed by the present study, we investigate the spatial distribution of the electric field in the storm-time inner magnetosphere. In order to investigate the two dimensional evolution of the inner boundary of the plasma sheet electrons as a function of the radial distance and local time, the analysis of the equatorward boundary of auroral activities will be useful.

本研究では THEMIS 衛星搭載の粒子計測器 ESA（ElectroStatic Analyzer）の観測データを用いて、磁気嵐の主相ならびに回復相におけるプラズマシート電子の内側境界の位置とエネルギー依存性を調べた。プラズマシートを構成する高エネルギー粒子は、磁気圏対流により磁気圏尾部領域から地球方向に輸送されるが、地球近傍では電子は朝側、イオンは夕方側へとドリフトすることとなり、一定の距離よりも内側には侵入できない。この動径方向の境界を inner edge と呼び、ドリフト軌道は粒子のエネルギーにより異なるため、inner edge の位置が粒子のエネルギーにより異なることが過去の研究により明らかとされている。Inner edge は大体 3 - 7 Re 付近に形成されている。プラズマシート粒子のふるまいは極域電離圏でのオーロラ活動とも密接に関連しており、磁気圏電離圏結合系を考える上で、プラズマシート粒子の空間分布とその磁気活動度依存性を明らかにすることは重要である。

過去の研究により、プラズマシートの inner edge の位置と地磁気指数との対応が議論されている。しかし、AE 指数との比較やローカルタイム依存性など、サブストーム時の inner edge についての報告例は多いものの、磁気嵐の各相での inner edge の位置や Dst 指数との関係については議論の余地が残されている。そこで本研究では、keV 帯のプラズマシート電子の inner edge に着目し、磁気嵐の主相ならびに回復相における inner edge について調べた。使用したデータは、THEMIS 衛星に搭載されている ESA(Electrostatic Analyzer) により取得された 1 keV から 10 keV のエネルギーレンジの電子フラックスデータである。まず、2013 年 7 月 6 日と 2012 年 6 月 17 日の磁気嵐中に同定された inner edge についてのイベント解析を行った。さらに、2007 年 3 月から 2013 年にかけて発生した磁気嵐 (主相 78 例、回復相 174 例) を同定し、各相での inner edge の位置について統計解析を行った。

イベント解析の結果から、inner edge の位置は磁気嵐の主相の方が回復相よりも地球に近い所に位置していることが示された。主相においてはおおよそ 3 - 4 Re 付近に形成されていた inner edge が、回復相では 4 - 10 Re 付近に位置していたことが示された。また Frank et al. [1971] によると、エネルギーの低い電子の inner edge の方が地球に近づくと報告されていたが、主相時の inner edge の位置には明確なエネルギー依存性が見られず、どのエネルギー帯でも同程度の位置に inner edge が同定された。一方で、回復相での inner edge は Frank et al. の結果と同様なエネルギー依存性を示していたが、規模の大きな磁気嵐時にはエネルギー依存性が見られないことが明らかとなった。以上の傾向は、統計解析の結果からも確認され、主相時の inner edge の典型的な位置は 3.9 Re 付近であることが明らかとなった。本研究により得られた結果は、磁気嵐主相では地球近傍に強い電場が存在することを示唆している。さらに本研究では、磁気嵐の相ごとに inner edge とオーロラの赤道側境界とを比較し、主相と回復相での対応関係の違いや、磁気嵐時に発生するサブストームの影響などについて議論する。

Van Allen Probes衛星観測結果に基づく小規模磁気嵐における放射線帯電子フラックス変動のエネルギー依存性についての研究

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The energy dependent enhancements of radiation belt electrons during moderate magnetic storms: Van Allen Probes observation

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By analyzing in situ observation data by Van Allen Probes, we study the spatial and temporal evolution of the flux of radiation belt electrons, the plasma environment, and plasma wave activities during moderate geomagnetic storms. It has been widely recognized that the radial distribution of the flux of electron radiation belts generally show two belt structures.. In September 2012, it was revealed that radiation belt electrons show three belt structures by observation of Van Allen Probes [Baker et al., 2013]. The formation process of three belt structures can be explained by considering loss processes of relativistic electrons when they are located outside the plasmapause. In general, when plasmapause moves inward during a magnetic storm, the flux of outer radiation belt electrons decreases during the main phase in the region outside of the plasmapause and increases again during the recovery phase. In the September 2012 event, since the variation of the plasmapause location is small, the region where the electron flux is strong remains inside the plasmashere and relativistic electrons are generated outside the plasmapause, resulting in the observed three belt structures. Since this three belt structure was observed during a moderate magnetic storm (Dst ˜-70 nT), we expect that the structures are often formed during a similar storm and that the role of the plasmapause location can be clearly identified by analyzing the formation process of the three belt structures.

In the present study, we analyze Van Allen Probes observation data measured during two storm events: 23 April 2013 and 25 May 2013 storms (hereafter we refer the former and latter events as event A and event B, respectively). The minimum Dst index is similar in both events; -49 nT for event A and -55nT for event B. We use the flux of relativistic electrons of 2.3 MeV, 3.6 MeV, and 4.5 MeV measured by the Relativistic Electron-Proton Telescope (REPT) [Baker et al., 2012]. We also analyze plasma wave and background magnetic field data measured by Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) [Kletzing et al., 2012].

During the both analyzed storm events, we find the flux decrease of outer radiation belt electrons in the region outside of the plasmapause, while we identify the location of plasmapause by analyzing the upper-hybrid resonance frequency from the wave electric field spectra of EMFISIS. In the recovery phase, we find the presence of the three belt structures in the event A but the usual two belt structures in the event B. During both events, the flux increases occur during both events in the region outside the plasmapause, while the location of the plasmapause is relatively closer to the Earth in the event B(L∗˜4 for event A, L∗˜3 for event B). We also analyze wave electromagnetic field spectra and identify the enhancement of whistler-mode chorus emissions in the region outside the plasmapause. We find that the activities of chorus emissions enhance concurrent with the timing of the flux increase of relativistic electrons, suggesting a close relationship between them. We also identified two-step enhancements of relativistic electrons during the event A. We find at the first step during the early recovery phase that the flux enhancement is measured only in 2.3 MeV and that the flux of 2.3-4.5 MeV increases simultaneously at the second step during the late recovery phase. To understand the identified energy dependence in detail, we analyze the correspondence between the flux enhancements and spectral characteristics of whistler-mode chorus by examining the cyclotron resonance condition under the observed plasma environment during the event. Furthermore, we analyze the phase space density of relativistic electrons in the inner magnetosphere so as to reveal whether the inward transport from outside or the acceleration process occurring in the inner magnetosphere is dominant as the mechanism of the observed flux enhancement.

本研究は Van Allen Probes 衛星によるその場観測結果に基づいて、小規模磁気嵐時における放射線帯電子フラックスの時空間変動とその物理過程について議論する。

地球の内部磁気圏には、放射線帯と呼ばれる、相対論的なエネルギーを持つ粒子が地球の磁場に捕捉された領域が存在する。特に電子の放射線帯については、相対論的電子フラックスの典型的な動径分布が、1.5 RE（RE は地球半径）でフラックスが最大となる内帯と、4.0 RE 付近で最大となる外帯とに分けられ、二つのベルト構造を成していると広く理解されている。一方で、2012 年 9 月の Van Allen probes の観測により、放射線帯電子が三つのベルト構造を示す例が報告された [Baker et al., 2013]。三つのベルト構造の形成過程は、プラズマポーズの位置に関連した相対論的電子の消失過程により説明される。放射線帯外帯を構成する相対論的電子のフラックスは、磁気嵐の主相において減少し、回復相に

おいて増加することが明らかとなっている。主相におけるフラックスの減少は、磁気圏の圧縮に伴う磁気圏界面からの惑星間空間への流出や、プラズマ波動との共鳴によりピッチ角散乱を受けることに起因した大気への降下と消失により説明される。また、回復相でのフラックスの増大は、磁気圏夜側からの動径方向輸送とそれに伴う断熱加速過程と、放射線帯領域で発生するプラズマ波動による加速過程によると考えられている。フラックスの消失過程と増加過程の双方に、プラズマポーズの位置が深く関与しているが、2012 年 9 月のイベントではプラズマポーズの位置の変動が比較的小さく、主相においてはプラズマ圏内にフラックスの強い領域が留まり、回復相においてプラズマポーズの外側で相対論的電子が生成され、その結果として三つのベルト構造が形成されたと考えられる。2012 年 9 月のイベントは小規模な磁気嵐 (Dst ˜-70 nT) であったことから、この構造は同程度の規模の磁気嵐時によく形成される可能性が考えられ、また、放射線帯の構造に対してプラズマポーズの位置が果たす役割を理解する上で重要な現象であると考えられる。

本研究では、2013 年 4 月 24 日と 2013 年 5 月 24 日に発生した磁気嵐での放射線帯電子の変動を議論する（以後、それぞれイベント A、イベント B と呼ぶ）。Dst 指数の最小値は、イベント A では-49nT、イベント B では-55nT である。解析には Van Allen Probes 衛星に搭載された Relativistic Electron-Proton Telescope(REPT)[Baker et al., 2012] による 2.3MeV,3.6MeV,4.5MeV のエネルギー帯の電子フラックス、ならびに Electric and Magnetic Field Instrument Suite and Integrated Science(EMFISIS)[Kletzing et al., 2012] によるプラズマ波動と背景磁場の観測結果を用いる。まず、両イベントについて、プラズマポーズの位置を波動電場成分のスペクトルから高域混成共鳴周波数を見出すことにより同定した。次に、相対論的電子フラックスの動径方向分布の解析から、イベント A では回復相において Baker et al. (2013) に類似した三つのベルト構造を呈するが、イベント B では通常の二つのベルト構造となっていることが示された。また、回復相においては両イベント共にプラズマポーズの外側でフラックスの増加が見られたが、プラズマポーズはイベント A で $L*\tilde{}4$、イベント B で $L*\tilde{}3$ と、イベント B の方が比較的内側に位置していたことが明らかとなった。さらに、両イベントにおけるプラズマ波動の電場成分の解析から、プラズマポーズの外側でホイッスラーモード・コーラス放射が励起しており、相対論的電子のフラックスの増加時にはコーラス放射の波動強度も増加していること明らかとなった。この結果は、両者の密接な関連を示唆している。また本研究では、イベント A の回復相において、相対論的電子のフラックスが二段階で増加していることを明らかにした。第一段階の増加は 2.3MeV のフラックスのみで起こり、第二段階の増加は 2.3-4.5MeV の広いエネルギー範囲で同時に生じていることが示された。エネルギー帯に依存したフラックス増加過程を理解するために、イベント発生時の内部磁気圏のプラズマ環境の詳細と、プラズマ波動のスペクトルならびにサイクロトロン共鳴条件を調べることで、コーラス放射とフラックスの対応を議論する。さらに、相対論的電子の位相空間密度の解析を行い、フラックスの増加を担う物理過程を明らかにする。

実験室プラズマにおける波動・粒子相互作用の直接観測実験

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Laboratory in-situ experiments for plasma wave-particle interaction

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Wave-particle interactions are thought to play important roles to generate MeV electrons in the radiation belt. 'Wave-Particle Interaction Analyzer (WPIA)', which derives energy flux between wave and particle from simultaneous measurements of an electric field and particle velocity vector, has been developed to observe the interaction between wave and particle in space plasma. We have been conducting two laboratory in-situ experiments for plasma wave-particle interaction as follows:

Topic #1 Application of a technique of Wave-Particle Interaction Analyzer to high-density laboratory plasma with drift waves, and Topic #2 Laboratory in-situ experiments for plasma wave-particle interaction in space plasma chamber.

In Topic #1, we have carried out the laboratory simulation using the Q_T-Upgrade Machine in Tohoku University, which is a linear magnetized plasma machine. The Q_T-Upgrade Machine consists of a vacuum chamber of 0.2 m in diameter and 4.5 m in length, and plasma sources, which generate high-temperature electrons using electron cyclotron resonance (ECR) and low-temperature thermal electrons. Thus, an electron temperature gradient (ETG) is formed in the apparatus by superposing low temperature thermal electrons on the high temperature electrons of the ECR plasma (n_e ~10^8 #/cc). Moon et al. [Rev. Sci. Instrum., 2010] reported that low-frequency drift-waves with a frequency of ~7 kHz were excited with ETG mode of ~0.5 MHz. We focus on the low-frequency waves and simultaneously measures an electric field vector (**E**) and current vector (**J**). Energy fluxes between wave and particle can be calculated from inner products of **E** and **J** vectors. For the simultaneous measurements, we have developed a combination probe, which is a combination of a Mach probe for ion flow measurements and a Twin probe for electric field measurements. Radial, tangential and axial components of **E** and **J** vectors are measured by rotating and tilting the probe in cylindrical plasma.

We will report an estimated structure of drift waves derived from multi-point and directional measurements of **E** and **J** vectors as well as transient response of wave growth in detail.

In Topic #2, we have been conducting laboratory simulation using a large space plasma chamber in ISAS/JAXA. By using a multi-cusp plasma source, which confines plasma to a multi-pole cusp magnetic field, the high density Argon plasma (n_e ~10^5-10^6 #/cc) is generated. The electron beam generated by applying a certain voltage difference between the two plasma sources excites electrostatic plasma waves. Also, a wave receiver and an electrostatic plasma analyzer installed in the chamber make it possible to simultaneously measure plasma waveforms and particle velocities, which are used to calculate the energy flux between wave and particle.

近年、ジオスペースにおける放射線帯の高エネルギー電子の起源として、プラズマ波動と粒子の相互作用による粒子加速過程が重要な役割を担っていると考えられている。この波動・粒子相互作用の観測を目的として、電場波動と粒子速度の同時観測から波動・粒子間のエネルギーフラックスを算出する波動・粒子相互作用解析装置 (WPIA: Wave-Particle Interaction Analyzer) の開発が進められている。現在、我々は、(1) 実験室プラズマに WPIA の観測手法を応用し、ドリフト波励起過程において波動・粒子相互作用の直接観測を試みる実験と、(2) WPIA 観測技術の実証・確立を目的とする、大型スペースチェンバー内の直接計測による波動・粒子相互作用の室内観測実験の 2 つの実験を進めている。

(1) については、直線型磁化プラズマ装置である東北大学の Q_T-Upgrade Machine を用いて行った。Q_T-Upgrade Machine は直径 0.2 m、長さ 4.5 m の円筒型真空チェンバーを用いた装置であり、チェンバー内の実験領域において ECR 放電による高電子温度プラズマ (n_e ~10^8 #/cc, T_e ~3 eV) と低温熱電子 (T_e ~0.2 eV) を重畳することで電子温度勾配 (ETG: electron temperature gradient) を形成することができる。電子温度勾配の制御により ETG モード (~0.5 MHz) が励起することを示した Moon et al. [Rev. Sci. Instrum., 2010] による実験では、ドリフト波モードの kHz 帯の低周波波動も同時に励起されることが報告されている。本研究ではこの低周波波動を対象に、電場ベクトルと電流ベクトルを同一点かつ同時に計測することで、それらのベクトルから波動と粒子のエネルギー交換量の算出を行う。計測には、電場ベクトル計測用のツインプローブと電流ベクトル計測用のマッハプローブを組み合わせたコンビネーションプローブを新たに開発し使用した。プローブを真空チェンバー内で可動させる機構を設けることにより、チェンバーの軸方向および動径方向、方位角方向の三成分ベクトルを計測可能である。

計測した電場ベクトルと電流ベクトルの内積演算から波動・粒子間のエネルギーフラックスの算出を目指しているが、現在は可動機構を用いて複数点で計測した電場波動と電流波動の位相関係を詳細に比較することで、低周波波動の三次元空間構造の推定を進めている。低周波波動はプラズマ源前方の 2 枚のグリッドの印加電圧を変化させ、プラズマ中の電子温度勾配を制御することで励起される。低周波波動が励起される前後のタイミングで電場及び電流の三成分計測を行うことで波動の成長過程も観測した。本講演ではこれらの解析結果について詳細を述べる。

(2) は JAXA 宇宙科学研究所の大型スペースサイエンスチェンバーを用いて行う。大型チェンバー内に同軸上に設置した４個の円筒型カゴ型プラズマ源により、生成した Ar プラズマを磁場で閉じ込め、10^5-10^6 #/cc 程度の高密度プラズマを生成させる。2 つのカゴ間に電位差を与えることで電子ビームを背景プラズマ中に生成し、カゴ内に静電波動を励起する。カゴ内に設置したプラズマ波動計測器と粒子分析器によりプラズマの電場波動と粒子速度の同時観測を試みる。

本講演では (1) の解析結果に加え、(2) の実験についても紹介する予定である。

磁場のない太陽風に対する地球磁気圏の応答

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The terrestrial magnetosphere under the solar wind with no interplanetary magnetic field

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It is generally believed that when the southward interplanetary magnetic field(IMF) impinges on Earth's magnetosphere, day-side reconnection and subsequent nightside reconnection drive magnetospheric convection that is so called the Dungey cycle appears. The Dungey cycle seems to persists even for northward IMF unless the IMF is close to purely northward when the reverse Dungey cycle appears. Although we thus know relatively well the apparent response of the magnetosphere to IMF changes, we do not know at all the Earth's magnetosphere when the solar wind has no magnetic field. When the activity of Sun becomes extremely weak like the Maunder minimum, it is considered that the solar wind has a vanishingly small magnetic field. In this study, we investigate the response of the Earth to a zero IMF solar wind using global magnetohydrodynamic (MHD) simulation. The numerical MHD modeling has an advantage in that it can simulate an ideal zero IMF case or a vanishingly small IMF case which are observationally difficult to handle.

Under a zero IMF solar wind,one may expect viscous cells with a potential drop of a few tens of kV. However, the remaining magnetospheric convection exhibits a cross polar cap potential much larger than the expected viscous cell potential. Thus, it is suggested that there exists another process of the driving mechanism other than the Dungey cycle or the viscous interaction. We elucidate the unknown element of the driving mechanism of magnetospheric convection.

惑星間空間磁場（IMF）南向きのとき、地球磁気圏の昼側では IMF と地球磁場のリコネクションがおこり、さらに夜側でもリコネクションがおこる。それによって地球磁気圏のプラズマ対流が駆動される。この循環はいわゆる Dungey サイクルとしてよく知られている。IMF が北向きであっても、“ 反転 Dungey サイクル ”の起こる純北向き IMF にならない限り、Dungey サイクルは維持される。そのようなほぼ常に存在する Dungey サイクルについては比較的よく知られているが、IMF が０になるとき（すなわち IMF がなくなるとき）、磁気圏で何が起こるかは全く知られていない。マウンダー極小期のような極端に太陽風活動が弱まるとき、太陽風磁場が弱くなることが予想されるが、場合によっては太陽風磁場が完全に０になることも考えられる。この時地球磁気圏では何が起こるのか。この研究ではグローバル MHD シミュレーションを用いて理想的な太陽風磁場０の状況を作り、それに対する地球磁気圏の応答を調べる。

磁場０の状況では数十 kV 程度のポテンシャル降下を伴う粘性セルが予想される。しかし、シミュレーション結果では、予想される粘性セルポテンシャルよりずっと大きいポテンシャル降下がみられた。そのことから、対流駆動要素に Dungey サイクルや粘性相互作用以外の存在が示唆される。その知られざる磁気圏対流駆動過程の解明をめざす。

ダイポラリゼーション・フロント周辺にみられる粒子速度分布関数の特性

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Characteristics of particle velocity distribution functions around the dipolarization front

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The leading edge of the bursty bulk flow is characterized by large northward magnetic field (Bz) and accelerated particles, and called dipolarization front. We investigate the velocity distribution functions of ions around the dipolarization front observed by Geotail spacecraft at X ~-10 Re (Re: Earth radius).

We found the earthward ion beams with widely spread pitch angles showing a crescendo-like shape. They seem to have larger pitch angles compared to the tailward ion beams frequently observed in the region beyond X ~-20 Re. At times, slower tailward ion beams with large pitch angles were present simultaneously with the earthward ion beams. The earthward ion beams are thought to be produced in the current sheet located at tailward-side of the spacecraft, while the tailward ion beams are due to the reflection of the earthward ion beams by the mirror effect in the off equatorial region.

We also observed the ion velocity distribution functions consisting of cold lobe ions and well-collimated ion beams near the dipolarization front. We will report on the association of various types of the ion velocity distribution functions to the structure of BBFs.

Burst Bulk Flow (BBF) の先端部は周辺よりも大きな北向き磁場成分（Bz）や加速されたイオン・電子によって特徴づけられ、ダイポラリゼーション・フロントと呼ばれている。本研究では、特に、Geotail 衛星が X~-10Re（Re: 地球半径）付近で、BBF を観測していた時のイオンの速度分布関数に焦点を当ててデータ解析を実施した。

その結果、ダイポラリゼーション・フロント領域においては、頻繁に、クレッシェンド型のピッチ角が大きく広がった地球向きのイオンビームの存在することが確認された。このビーム成分は、X ~-30Re 以遠に出現する反地球向きの BBF でみられるものに比べて、ピッチ角が大きい傾向がある。また、ある時間帯では、それよりも低速であるが、やはりピッチ角の広がった反地球向きのイオンビームが確認された。地球向きのイオンビームは、より尾部側の領域で加速されたものであり、そのビームが磁力線に沿って運動すると、ある地点で磁気ミラー効果によって運動の向きを反転させて赤道付近に戻り、それが反地球向きのイオンビームとして観測されることが予想される。

一方、ダイポラリゼーション・フロントの中で通常のプラズマシート境界層でみられるようなローブ起源の低温なイオンと遠方で加速されたピッチ角の狭いイオンビームが共存している速度分布関数も観測された。

本講演においては、それらの速度分布関数の特性と BBF の構造の関連について報告を行う。

Substorm electric fields at mid-latitudes and equatorial electrojets on the nightside

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The convection electric field increases during the growth phase of substoms, driving the DP2 currents and leading to an increase in the eastward equatorial electrojet on the dayside (EEJ). By analyzing isolated substorms with magnetometer network and SuperDARN data, we have shown that the electric field and currents are often reversed in direction, i.e., overshielding occurs at subauroral to equatorial latitudes causing the CEJ on the dayside during the substorm expansion phase. In order to examine the overshielding electric fields on the nightside, we analyze HF Doppler sounders data at low latitude stations Oarai and Sugadaira in Japan. The Doppler frequency of the HF radio signals at 5 and 8 MHz represents vertical plasma drift of the ionospheric F region due to zonal electric fields. We found that the westward (overshielding) electric field reaches around 2 mV/m on the nightside during substorm expansion. Taking the geometrical attenuation into account, we estimate the equatorial electric field to be about 1.5 mV/m. By comparing the HF Doppler data with the equatorial EEJ/CEJ, we also found that the correlation coefficient was 0.94 between the overshielding electric field and eastward equatorial electrojet at YAP on the night side. The overshielding electric field drives the westward and eastward electrojets in the equatorial ionosphere on the day- and night-side, respectively. These results suggest that the overshielding electric field associated with the Region-2 field-aligned currents becomes dominant during substorms at low latitude on the nightside as well as on the dayside.

小型電磁界センサープローブの地上実証実験に向けた設計開発

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Design and development of the small electromagnetic sensor probe system for the evaluation experiment

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The present paper shows the achievements in designing and developing the small sensor probe system dedicated to the measurement of electromagnetic waves. The proto-type model we will make is used for the evaluation experiment on the ground. We have been developing the one-chip plasma wave receiver for the purpose of miniaturization of plasma wave instruments. The sensor probe system makes use of the miniaturized plasma wave instrument. The plasma wave receiver chip is implemented inside the small body of the sensor probe as well as other peripheral devices such as a CPU, and small wireless communication device.

In the evaluation experiment, the waveform capture chip which our study group miniaturized is installed in the sensor probe. The sensor probe has four functions. They are: 1. Extension of the electric field sensors remotely by a command, 2. Measurements of the JJY standard signal as the measurement target, 3. Detection of the attitude of the sensor probe, and 4. Transmission of the observed data by using wireless LAN devices. The purposes of this experiment is evaluation of the self-extending antenna, the waveform capture chip, and the small sensor probe system.

The sensor probe has dipole antennas and loop antennas which can measure three-axial data of electric and magnetic fields. The chassis of the sensor probe is a cubic body with an edge of 9cm and it needs many electric components. As the CPU of the sensor probe, we selected a very simple CPU, so-called dsPIC, in which A/D converter was installed. We designed A/D converter which has four simultaneous sampling to meet requirements which is determined from the sensitivity of antennas and the electromagnetic intensity of measurement target. As the attitude sensor, we use the small magnetic sensor which measures the three-axial intrinsic magnetic field. From the data, we can know the attitude of the sensor probe. They are transmitted to dsPIC by I2C communication. Installing the program to dsPIC and wireless LAN devices, we realized data transmission by radio communication.

In our poster, we show the evaluation of the small sensor probe system we designed and the result of the evaluation experiment.

科学衛星ミッションの高度化などにより搭載する観測器の小型化が求められている。一方、この小型化された観測器と通信などの周辺装置を小型の筐体に収めたセンサープローブを用いて、科学衛星では不可能な「多点同時観測システム」を実現することも可能である。我々の研究グループでは小型電磁界センサープローブの実現に向けて、特定用途向け集積回路 (ASIC) 技術を用いてプラズマ波動受信器のワンチップ化に取り組んでいる。一方、センサープローブを実現するためには、ワンチップ化されたプラズマ波動受信器ばかりではなく、観測システムを制御する CPU、観測データを伝送する無線システム、センサープローブの姿勢捕捉、および、これらを支える電源システムが必要である。本研究発表では、この小型電磁界センサープローブのシステム設計、および、機能を制御するソフトウェアの開発の観点で、そのシステムの実現に向けた地上試験のためのプロトタイプモデルについて発表を行う。

現在、小型センサープローブの地上での実証実験が計画されている。センサープローブ本体は 9cm 角の筐体であり、3 軸の自己展開型ダイポールアンテナ (1.6m tip-to-tip) とループアンテナ (1 辺 12cm, 100turns) を有している。受信器にはワンチップ化した波形捕捉受信器を用いる。実証実験では、ダイポールアンテナのコマンド制御による自己展開を行い、観測対象である 60kHz の JJY 標準電波の電磁界 6 成分の観測を行う。観測した電磁界データはセンサープローブの姿勢データと共に無線によるデータ伝送を行う。

センサープローブには、コマンドによる遠隔制御でのダイポールアンテナの展開、電磁界 6 成分のデータ取得、姿勢データや HK の取得、無線データ伝送の 4 つの動作が求められ、これらの動作を支えるシステムを、9cm 角の筐体内にすべて収める必要がある。そのため搭載するプラズマ波動受信器以外の機器も可能な限り小型・軽量なものを選定した。センサープローブの CPU 及び A/D 変換器として、Microchip 社製のワンチップマイコンである dsPIC を採用した。採用した dsPIC は 4ch 同時 A/D 変換が可能であり、これを用いて電磁界それぞれ 3 成分の同時刻のデータの取得を行う。要求されるサンプリング周波数と連続サンプリングデータ数は、センサーのノイズレベル及び観測対象の JJY 標準電波の周波数と信号強度から設計する。得られた要求値を満足できるよう、サンプリング周波数 220kHz、連続サンプリングデータ数 950 個の 4ch 同時 A/D 変換を設計し、dsPIC にプログラムを実装した。また、波形捕捉受信器のゲイン及び電磁界選択の切り替えを dsPIC によって行えることを確認し、波形捕捉受信器によってチャンネル間に生じる位相差の測定も行った。多点観測システムの実現には、センサープローブ自体の位置及び姿勢を知ることが重要となる。姿勢センサーとして、地球磁場を 3 軸計測可能な磁気センサーを用いた。これによりセンサープローブの位置及び向きを知ることができる。磁気データは I2C(Inter-Integrated Circuit) 通信を用いて dsPIC へと伝送するプログラムの実装を行う。dsPIC の UART 機能を用いることで電磁界データと姿勢データを小型無線器に出力し、2.4GHz の高周波信号を用いた無線通信を

行う。dsPIC からのデータ出力と、無線器間通信のプログラムを両者に実装した。なお、実証実験では送信側のアンテナにはパッチアンテナを用いる予定である。また、データフォーマットを考案し、その実装も行う。

本発表では、上記のセンサープローブに実装した各動作の評価及びシステム全体の評価について述べる。また、実証実験の結果についても述べる予定である。

ロングイアビン・オーロラスペクトログラフによるオーロラ・大気光の長期分光観測

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Long-term spectral observations of aurora and airglow in Longyearbyen, Svalbard

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Auroral/airglow spectrograph (ASG) observations in Longyearbyen Svalbard have been conducted since October 2000. The ASG consists of a large fish-eye lens, a slit which passes the light from the sky along geomagnetic meridian direction, a grism with 600 gr/mm, and a cooled CCD camera. The ASG covers a wavelength of about 420-760 nm with spectral bandwidth of 1.5-2.0 nm. Analysis of the ASG data over 1 solar cycle shows that intensity of 630.0 nm emission exceeds that of 557.7 nm around 12 MLT during high solar activity, whereas intensity of 630.0 nm emission is weaker than that of 557.7 nm even in the dayside during low solar activity. They would be related to the relative locations of the cusp and ASG. In addition, there is a weak peak of H beta emission (486 nm) around 14 MLT. In this paper, we give an overview of the spectral observations and statistical results of auroral intensity at each wavelength over 1 solar cycle.

Table 1. Summary of the auroral spectrograph observations in Longyearbyen, Svalbard.

Start year & month	End year & month	Number of images	Wavelength (nm)
2000-10	2001-02	39000	450-760
2001-10	2002-03	33000	450-760
2003-01	2003-03	21000	425-735
2004-01	2004-03	22000	450-760
2004-12	-	2000	450-760
2005-11	2005-12	8000	450-760
2007-12	2008-03	17000	420-730
2008-11	-	4000	420-730
2009-12	2010-03	46000	430-740
2010-10	2011-03	81000	420-730
2011-10	2012-03	78000	420-730
2012-10	2013-03	99000	420-730
2013-10	2014-03	84000	420-730

地球磁気圏尾部領域における電子異方性の生成

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Generation of electron anisotropies at dipolarization sites

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Anisotropic electron distributions are often found in the earth's magnetotail, in the energy range from about 10eV to 10keV [1]. Theoretical models are proposed to account for these distributions, based on parallel (Fermi) and perpendicular (betatron) electron heating due to deformation of the magnetic field lines [1,2]. When typical parameters are used for the magnetic field and the electron energy, the first adiabatic invariant (magnetic moment) is always conserved while the second invariant (action associated with the bouncing motion along the field lines) can be violated depending on the electron energy.

Recently, Wang et al (2014) made a statistical analysis on variation of electron pitch-angle anisotropies during geomagnetic dipolarization events using THEMIS data. They found that, after the dipolarization, pancake type (perpendicular temperature > parallel temperature) anisotropy increases when the electron energy E < ~1keV, while cigar type (perp < parallel) anisotropy dominates for E>~1keV.

When both the first and the second invariants are conserved, types of anisotropy produced by compression of the field depend only on the shape of the magnetic field configuration. If the field remains dipolar, pancake type will be produced. If the magnetic field lines are stretched like those in the magnetotail, cigar-type anisotropy will be produced since compression (earthward motion) of the field reduces the field line length without much changing the field strength. In this presentation we show our results of test particle simulations to discuss what types of pitch-angle anisotropies would emerge for various field line configurations. In particular, we show that the observed dependence of the types of anisotropies on the electron energy can roughly be explained in the present model.

[1] Hada et al., JGR, 1981; Shiokawa et al., Ann. Geophys. 2003; Wang et al., JGR submitted, 2014.
[2] Smets et al., JGR, 1999; Sergeev et al., GRL,2001.
[3] Wang et al., JGR submitted, 2014.

磁気圏尾部領域には 10eV から 10keV 程度のエネルギーにおいて、異方性を持った電子分布が出現することが知られている [1]。これらの成因として、この領域の磁力線変形により、磁力線に平行方向と垂直方向とで電子が異なる加速を受けるモデルが提案されている [1,2]。このモデルにおいて、断熱不変量の保存・非保存が重要である。周知のように、地球磁場中での荷電粒子の運動は 3 種の周期運動（サイクロトロン、ミラー、ドリフト）の重ね合わせとしてほぼ表現でき、それぞれに断熱不変量が定義できる。これらの運動はオーダーの全く異なる周期を持ち、第 1 不変量（磁気モーメント）はどのような状況でもほぼ保存されるが、第 2 不変量（沿磁力線ミラー運動の伴う作用）の断熱性は、外力のタイムスケールと電子のエネルギーに依存して決まる。

最近、Wang et al (2014) は THEMIS 衛星のデータを用いて、磁気圏尾部の磁場の dipolarization に伴う電子ピッチ角分布の変動を解析した [3]。統計解析の結果によれば、出現する異方性は電子のエネルギーに依存し、1 keV 程度よりも低いエネルギーでは dipolarization に伴ってパンケーキ型（垂直温度＞平行温度）の異方性、1kev 程度よりも高いエネルギーではシガー型（垂直＜平行）の異方性が形成されることが明らかとなった。

第 1 不変量、第 2 不変量ともに保存される場合には、ダイポール磁場がその形を保ったまま圧縮されたときに形成されるのはパンケーキ型、尾部方向に引き延ばされた磁力線上の電子の場合にはシガー型が形成される。しかし第 2 不変量の保存は電子エネルギーに依存するため、形成される異方性にもエネルギー依存性が現れることが期待される。本研究では、地球磁気圏内における電子の運動をテスト粒子計算により解析し、外部電場によって磁気圏が圧縮された場合にどのような異方性が出現するか、電子エネルギー依存性に注目して解析を行い、Wang et al の観測結果がほぼ説明できることを示す。

参考文献

[1] Hada et al., JGR, 1981; Shiokawa et al., Ann. Geophys. 2003; Wang et al., JGR submitted, 2014.
[2] Smets et al., JGR, 1999; Sergeev et al., GRL,2001.
[3] Wang et al., JGR submitted, 2014.

A new explanation for the asymmetries of equatorial east-west electric field based on the global polarization effect

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The longitudinal profile of the east-west electric field in the equatorial region shows characteristic such as morning-evening asymmetries with pre-noon peak and localized enhancements around the dusk sector (pre-reversal enhancement, PRE). Although these structures have been discussed in terms of the neutral wind dynamo, we propose that it is also possible to explain them, at least qualitatively, purely by ionospheric effects.

Our study is based on the idea of the global Cowling Channel (or the global polarization theory) [Yoshikawa, JpGU, 2011]. So far, we have specified one-to-one relationship between some characteristic inhomogeneities of conductivity and characteristic deformations of electric potential based on model calculations. For example, considering a dawn-dusk symmetric R1-FAC distribution for simplicity and defining its primary field as Phi_0, (a) equatorward conductivity enhancement yields positive/negative Hall polarization field ($\mathrm{dPhi}_{Hall,eq}$) around pre-noon/pre-midnight sectors and rotates the two-cell potential pattern clockwise, (b) day-night conductivity difference shifts the potential maximum and minimum toward night due to the Pedersen polarization effect (in other words, current continuity), and (c) sharp conductivity gradients across dawn/dusk terminators result in positive/negative Hall polarization field ($\mathrm{dPhi}_{Hall,t}$) and convex/concave of potential along the terminators.

Guided by the above exercise we seek to understand the east-west electric field structure in the equatorial region. The morning-evening asymmetry with pre-noon peak is naturally produced by the effect (a). PRE like structure can be produced basically by (c), but its sharpness is determined by the total balance of (a), (b), and (c), which can be attributed to the relative distributions of background and auroral zone conductivities. In this talk we will also discuss the possibilities to distinguish ionospheric polarization effects from atmospheric effects.

Study of bursty bulk flow reversals using MHD simulations and satellite observations

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Tailward flow in the near-Earth plasma sheet associated with a rebound of the earthward bursty bulk flow (BBF) is investigated using three-dimensional magnetohydrodynamics simulations of magnetic reconnection in the magnetotail on the basis of the spontaneous fast reconnection model and GEOTAIL satellite observation data. In order to investigate the properties of this tailward flow, virtual satellites are located at different positions in the plasma sheet within the simulation region, so that we can directly observe the temporal variations of plasma quantities in accordance with the growth and preceding the flow reversal associated with the magnetic reconnection, and compare with satellite observation data. As a result of the rebound of the earthward flow, the accumulation of the plasma density and the plasma pressure is observed at any position in the plasma sheet during the interval between the BBF and the reverse flow.

アラスカポーカーフラットにおける地上光学観測による酸素原子630nmオーロラの偏光特性

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Characteristics of 630nm auroral polarization observed at Pokar Flat, Alaska

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We report the result of OI 630 nm auroral polarization observation at Poker Flat Research Range (Glat=65.12N, Glon=147.43W, Mlat=65.72N) during the period from December 2013 to April 2014. OI 630nm auroral emission is theoretically expected to show linear polarization with degrees up to 17% [Bommier et al., 2011]. The important point is that, the degree of linear polarization depends on energy and velocity anisotropy of precipitating electrons [Fujimoto et al., 1997]. Recent observation data also showed that 630nm auroral emission related to polar rain at high-latitudes linear polarization parallel to field with degrees of 2-7%[Lilensten et al., 2013]. However, these past measurements were limited in the polar cap region and its polarization characteristics are not clear.

To examine auroral polarization with an accuracy of 1% polarization degree, we developed an imaging spectrograph which can measure auroral polarization in the wide field-of-view of 130 deg covering the wavelength range from 420 nm to 680 nm (resolution 2 nm). This new instrument enables us to obtain the linear polarization degrees at 557.7 nm and 630 nm auroral emissions simultaneously. Here, we can regard 557.7 nm aurora as a standard polarization light source because it does not produce polarization theoretically. We installed the spectrograph at Poker Flat and carried out precise calibration to estimate artificial polarization which is produced inside the optical system using an LED light source with a linear polarizer every 3 hours on five nights in December 2013. Since then, automatic operation was continuously carried every night out till the beginning of April 2014.

We obtained the linear polarization of 630 nm aurora with degree of 5% showing elevation angle dependence. On the other hand, we unexpectedly measured the polarization of 557.7 nm emission which shows similar polarization property as 630 nm. We are considering two possibilities to interpret the results as follows. First is that the auroral emissions are additionally scattered and polarized through atmospheric particles and dusts in the middle and lower altitudes in the line-of-sight direction. Second is that we could not correct instrumental artificial polarization effect with the calibration we did last year and further accurate calibration will be required.

In the future, we discuss the fluctuation of pitch angle distribution with auroral activity from the results.

Study of the resonant interactions of relativistic electrons and large-amplitude whistler-mode waves

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We carry out test particle simulations of relativistic electrons interacting with obliquely propagating large-amplitude whistler-mode waves in the Earth's inner magnetosphere. Recent observation revealed large-amplitude whistler-mode waves propagating obliquely with respect to the ambient magnetic field [Cattell et al., 2008]. Yoon [2011] suggested that the observed large-amplitude whistler-mode waves can contribute the energization of radiation belt electrons to relativistic energies (MeV) within a few seconds. However, details of the acceleration process by oblique whistler-mode waves have not been understood yet. In the present study, by referring observation results of large-amplitude whistler-mode waves in the magnetosphere, we discuss resonant interactions between oblique whistler-mode waves and relativistic electrons.

The cyclotron resonance is dominant in the interactions between resonant electrons and whistler-mode waves propagating parallel to the background magnetic field, while the Landau resonance should also be taken into account for obliquely propagating whistler-mode waves.

For the study of resonant interactions, we develop a test particle simulation code to solve the motion of energetic electrons under the presence of whistler-mode waves. We first assume monochromatic whistler-mode waves of frequency of 0.2 fce, where fce is the electron gyrofrequency. The wave amplitude is constant in time and assumed to be 1 % of the intensity of the background magnetic field. We assume relativistic electrons having the initial kinetic energy of 0.66 MeV with various initial pitch angles and gyro-phases. The time scale of the simulation is 100000 gyro-periods, corresponding to 0.95 sec for the parameters at L=4 of the Earth's magnetosphere. For the case of monochromatic whistler-mode waves propagating purely parallel to the background magnetic field, a part of resonant electrons are trapped by the waves and oscillate in the velocity phase space. The width of the oscillation in the velocity phase space can be estimated by the trapping velocity. We estimate that the trapping velocity is typically less than 0.01% of the initial velocity of the relativistic electrons under the condition assumed in the present study, which is consistent with the simulation result. Next, we carry out a series of simulations by changing the wave normal angle of whistler-mode waves. In these simulations, Landau resonance with the longitudinal wave component occurs simultaneously with the cyclotron resonance. We find that higher-order cyclotron resonances also occur in the simulation results and that the magnitude of the oscillation of electrons resonating with the oblique whistler-mode wave is not larger than that in the case of parallel propagating whistler-mode waves. The results of the present study clarify that the developed test particle code is useful for the quantitative evaluation of the energizing process of relativistic electrons by whistler-mode waves of arbitral wave normal angle. By conducting simulations for various properties of whistler-mode waves such as the wave frequency and wave amplitude, we investigate the effect of the wave characteristics on the resonant interactions between relativistic electrons and large-amplitude whistler-mode waves.

準天頂衛星からのTECデータを用いたプラズマ圏境界の推定に関する検討

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Feasibility study of estimation of plasmapause location using QZS-TEC

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We examined a feasibility to detect the plasmapause location by using TEC observations from GPS and QZS. It is difficult to distinguish the influence of ionosphere and plasmasphere is from GPS-TEC only. Using a global density model, we examined the parameter dependence of difference between GPS-TEC and QZS-TEC.

プラズマ圏境界の位置は、内部磁気圏の擾乱の度合いを示す指標の一つとされる。本研究では、GPSおよびGPS互換の準天頂衛星 (QZS) から送信された信号の遅延量から算出される2つのTotal Electron Content (TEC) の差を基に、プラズマ圏境界の位置を定常観測する手法について検討した。

通常、GPSの2周波信号で測定される衛星-地上間のTECにおいて、電離圏とプラズマ圏の影響を切り分けることはできない。これに対し、GPSよりも高高度約36,000kmの軌道を飛翔する準天頂衛星からのTECとGPS-TECとの差を求め、その差が様々なパラメータに対してどう変化するかを、グローバルな電子密度分布モデル (GCPM) を用いてモデル計算した。ただし、GPS衛星とQZS衛星と観測点が厳密に一直線上に並べばGPS-QZS間の正確な電子密度を得ることができるが、実際にはそのような条件を満たすことは難しく、そのずれの影響も考慮する必要がある。この経路の違いによる影響は主に電離層電子密度に起因するが、この影響がTECの観測誤差以下になるような条件について調査を行った。ここで、観測誤差として受信機のDifferential Code Bias (DCB) のみを想定した。本発表ではプラズマポーズの位置の検出が可能なパラメータ (ローカルタイム、通年日、太陽活動度) 範囲について報告する。

あけぼの衛星で得られたVLF/WBA波動データへのクラスタリングの適用

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Automatic classification of plasma waves observed by the Akebono VLF/WBA

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In this study, we developed an automatic classification method of wave data obtained by the VLF/WBA instrument on Akebono satellite. Distinctive fine structures of various wave phenomena can be seen in spectrograms from the WBA data. We classified each wave according to such fine structures. The classification is based on clustering methods that do not need prior information about each wave. We compared results by two clustering methods; k-means and mixture Gaussian model and found that the Gaussian model classified each wave better.

1989年に打ち上げられたあけぼの衛星は、25年目を迎えた現在でも運用を継続しており，観測データは大規模なデータセットとして蓄積されている．このあけぼの衛星の特徴的な観測として，14 kHz以下の低周波のプラズマ波動の「波形観測」があげられる．近年の科学衛星による波形観測が，波形をオンボードでサンプリングして圧縮/選別処理等を施した後，地上に伝送するのが一般的となっているのに対して，あけぼの衛星では波形をそのままアナログテレメトリに載せて地上に伝送するという観測手法がとられている．このため，取得したデータはSNが悪いという欠点はあるものの，優れた時間継続性や周波数分解能をもち，他の衛星にはない貴重なデータを提供している．現在では，あけぼの衛星から得られた波形データ（WBAデータ）の有効活用が，衛星の継続運用の目的のひとつとなっており，今後の幅広いユーザーの利用のために，一次処理，二次処理を速やかに実現する支援ツールの整備が必要不可欠である．

近年の計算機の進化によって巨大データ（ビッグデータ）から知識発見を行ういわゆるデータマイニング法の研究が飛躍的に進んだことにより， 先述のあけぼの衛星の波形データセットに対しても，これまでの計算機資源では難しかった大規模な波動の分類（クラスタリング）を適用する環境が整った．プラズマ波動は，発生メカニズムや伝搬過程に応じてホイスラ，コーラス，ヒス，EMICなど多種に分類されるが，実際には，観測波動の周波数スペクトルの形状や定性的な変化に基づいて分けられている．これは発生・伝搬過程と周波数スペクトルの間に強い相関関係があるためである．ただし，こうした分類は明確な定義に基づいて行われている訳ではない点に注意が必要である．これに対して，本研究では，波動の微細なスペクトル構造を多次元の特徴量ベクトルとして定量化して，それらの類似度に基づいて分類することにより，各種波動を帰納的に分類する手法を確立することを目指している．クラスタリングを用いることで，教師あり学習やパターンマッチング等と比較して，先見的な知識なしに波動の特徴を定義できる．

クラスタリングの具体的な実現手法として，確定的な分類を行うk-means法と確率的な分類を行う混合ガウスモデルについて，その分類結果の違いについて検討した．k-means法はデータ数の1次のオーダーで計算が完了する高速な分類法であり，大規模なデータに対する処理も容易である．一方で，初期クラス中心の位置によって得られる結果が変化することや，クラスタが多次元特徴量空間上で超球状の形状になるために，クラスタに属するサンプル数がどれもほぼ等しくなるという制約がある．今回，対象としているデータの波動分類においては，ノイズ成分が非常に多く，分類すべき波動の割合がノイズに比べて少ないため，k-means法では，ノイズ成分の一部が波動と混在してしまうという結果になった．また，データには複数の波動が混在した箇所があるが，k-means法は確定的な分類法のため，そのような箇所は特定の波動として分類されてしまった．

混合ガウスモデルでは，多次元空間上の分布を多変量正規分布の和で表すことにより，より柔軟なクラスタが形成される．また，分布の重なりでデータを表現するため，複数の波動を表現できる利点がある．計算時間についてはk-means法より劣るものの，パラメータ推定のための近似アルゴリズムが複数提案されており，今回は変分ベイズ法を用いた．結果として，サンプル数の少ない波動と，サンプル数の多いノイズをきっちりと分類することができた．結果として、WBA波動データを分類する手法として混合ガウスモデルの方が適切であることが確認された．今後は得られた波動に対して，そのスペクトル形状から定量的な定義づけを行う予定である．

Evaluation of waveform data processing in Wave-Particle Interaction Analyzer

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The Wave-Particle Interaction Analyzer (WPIA) is a software function installed on the Exploration of energization and Radiation in Geospace (ERG) satellite. The WPIA directly measures the quantity of energy transfer between whistler-mode chorus waves and resonant energetic electrons by using plasma wave vectors and velocity vectors of

plasma particles. The phase differences of the WPIA require accurate phase angles of waves and electrons in order to statistically evaluate the significance of the quantity of energy transfer. We propose a technical method for efficient waveform processing in order to conduct the WPIA measurement precisely. In the WPIA measurement, the various waves detected by the onboard instrument appear as noise in the calculation of the quantity of energy transfer for whistler-mode chorus waves. The characteristic frequency variation of the chorus waves makes waveform processing difficult. A chorus waveform is used for the WPIA processing through passband filtering by selecting appropriate data processing length and frequency resolution. We implement overlapping processing of wave data in order to reduce the induced error of the wave phase. The results of waveform processing indicate that the phase errors are successfully reduced and statistical fluctuations are suppressed. The proposed waveform processing method is a necessary and applicative processing for the calculations of the WPIA in the ERG mission.

Statistical characteristics of MF/HF auroral radio emissions emanating from the topside ionosphere

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The terrestrial auroral ionosphere is a natural emitter of electromagnetic waves in the MF/HF ranges (up to 6 MHz) as well as well-known intense auroral kilometric radiation (AKR) and auroral hiss in the VLF/LF ranges. We report on the statistical properties of Terrestrial Hectometric Radiation (THR), MF/HF auroral radio emissions emanating from the topside ionosphere, using a long-term data set obtained from the Plasma Waves and Sounder (PWS) experiment mounted on the Akebono satellite during 2 solar cycles. THR typically occurs in either or both of two frequency bands near 1.5-2.0 MHz and 3.0-4.0 MHz, whose polarization features correspond to the L-O and R-X mode. Statistical studies using the Akebono/PWS data reveal clear bimodality in the frequency distribution of THR with two broad peaks near 1.6 MHz and 3.6 MHz. Occurrence rate of THR-L (lower than 2.5 MHz) is higher than that of THR-H (higher than 2.5 MHz). Solar activity dependence and seasonal variations of THR appearance are manifested; THR occurrence rate drops from a few percent during solar maxima to 0.1 percent or less during solar minima and is the highest in summer and the lowest in winter. This study also shows the spatial distribution of occurrence rate of THR-L and THR-H. In the morning to postnoon sectors (3h-15h MLT), the spatial distribution of both types of THR is confined to magnetic latitudes higher than 70 deg, while during nighttime (15h-3h MLT) it spreads to lower magnetic latitudes (˜30 deg) at higher altitudes. The explanation of this distribution is that THR is generated in the night-side auroral latitudes near 1000-km altitude and propagation effect makes an emission cone.

0.01-25keV/q ion mass spectrometer (LEPi) to be onboard ERG spacecraft

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We are developing a low-energy ion mass spectrometer to be onboard ERG spacecraft. ERG is a scientific spacecraft which explores dynamics of terrestrial radiation belt. LEPi is one of the particle instruments onboard ERG. Its energy range (0.01-25keV/q) covers ions which are believed to play a significant role on excitation of magnetosonic waves and EMIC waves in the radiation belt. However, measurements of plasma partciles with energies lower than 100keV is not easy in the terrestrial radiation belt, since fluxes of high-energy particles are large. High-energy particles can penetrate through, or kick out the secondary particles when they hit materials. This means they can be detected by a detector inside an instrument without any analysis, namely, noise. In order to reduce the noise generated by the high-energy particles, we apply a time-of-flight (TOF) technique. In addition, we try to minimize size of the detector. We will present performance of LEPi and status of flight model fablication.

Study of Pitch Angle Distribution in the Earth inner Magnetosphere; Clue of Magnetopause Shadowing

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The Earth's Radiation Belts consist of two regions, and these regions accommodate highly energetic electrons. Especially in the outer radiation belt, the energetic electron is highly variable during magnetic storm time. Energetic electrons sometimes cause satellite charging, resulting in gradual degradation of the instrument and devices of the satellite. It is, therefore, imp tant to understand basic physics of the energetic electron variation in the radiation belt from the space weather point of view. It is considered that the drastic change of outer radiation belt is the result of competition between each variation processes, i.e. Transport, Acceleration and Loss. However, each process has complex physical mechanisms and there remain still much outstanding questions.

In this study, we particularly focused on the Loss Process. As a possible loss process, (i)Precipitation to the atmosphere, (ii)Dst-effect and (iii)Direct Loss from the magnetopause (Magnetopause Shadowing) are supported. According to the recent study, it is reported that rapid depression of outer radiation belt's electron flux is the result of the sudden inward shift of Magnetopause and subsequent enhancement of outward radial diffusion (Turner et al., 2012). And the relationship between Magnetopause location and outer radiation belt is studied by Matsumura et al., 2011. However, the regions, where electrons will escape or the Magnetopause effect will reach, are still undefined questions. In order to understand the effect of Magnetopause, we used the theory of drift shell splitting. Due to the asymmetric configuration of Earth's Magnetosphere, charged particles which has different pitch angle drift different drift shell. This means that particle whose pitch angle is closed to 90 degree drifts more close to the Magnetopause. It is, therefore, expected that the pitch angle distribution will be the butterfly distribution, as a result of Magnetopause Shadowing. To confirm this theory, we used Solid State Telescope onboard THEMIS satellite and analyzed pitch angle distribution. Butterfly distribution is usually seen at night sector in magnetically quite time. However, our result shows clear differences of electron's pitch angle distribution between each magnetic storm phase. We consider that this change is caused by the effect of inward shift of magnetopause.

Properties of energetic ion PSD during storm-time substorms observed by Van Allen Probes

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It is believed that ion injections from the magnetotail caused by substorms is one of the principal mechanisms that supply energetic ions to the magnetosphere ring current.However, it is not fully understood how deeply into the inner magnetosphere (i.e., inside the geostationary orbit) ions can penetrate.In this study, to characterize the supply of energetic ions to the ring current during a magnetic storm, we investigate the properties of energetic ion phase space densities (PSD) during storm-time substorms observed by the Van Allen Probes mission during magnetic storms that occurred in the period from April 23, 2013 to May 6, 2013.Using energetic ion (greater than 50 keV) and magnetic field data obtained by the RBSPICE and EMFISIS instruments onboard the Van Allen Probes, we examine the temporal variations of ion PSD spatial distributions in the L direction.

We obtained PSD and the first adiabatic invariant, mu, for ions with pitch angles of 70 to 110 degrees, as follows.First we calculated the ion energy perpendicular to the magnetic field from the total energy and pitch angle data, and then divided the perpendicular energy by the magnitude of the magnetic field.We also divided the ion differential flux by the perpendicular energy to derive PSD.Finally, we derived PSD for specific mu = 0.3, 0.5 and 1.0 keV/nT.This analysis provides the time variations of ion PSD with a certain mu value in the L distribution for each orbit of Van Allen Probes observations.

Preliminary results show that ions did penetrate directly down to L less than 5 at the time of substorms during the main phase of magnetic storms (which are relatively small, with the minimum Dst greater than -65 nT).Ions with smaller mu values (mu = 0.3 and 0.5 keV/nT) are found to penetrate more deeply than those with a larger mu values (mu = 1.0 keV/nT).The ion PSD distribution along L displays a sharp gradient at L ˜4.0 to 4.5 and L ˜3.0 to 3.5.In our presentation, we will also present differences between the PSD for protons and oxygen ions, and the dawn-dusk asymmetry of the L profiles.

Influences of possible grand minimum on cusp latitude

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The current unusual solar cycle is thought possibly to be the beginning of so-called Grand-Minimum period when solar activity stays at a low level for a considerably long period. If this is the case, geospace environment (e.g., solar wind energy input and distribution of high energy particles) might change largely and consequently resulting in e.g., less frequent storms and substorms, shrunk polar cap and auroral oval and unexpected environmental changes in upper atmosphere or even climate changes. Such a view is one of the important scientific issues in new SCOSTEP VarSITI program (2014-2018).

SuperDARN HF radar network is a powerful tool to monitor fundamental ionospheric physical parameters to investigate global electric potential maps and the dynamics of ionospheric and magnetospheric plasma convection under a variety of solar wind and magnetospheric/ionospheric conditions.

SuperDARN HF radar network and various ground-based electro-magnetic field/waves and optical instruments at manned and unmanned stations have been deployed in Antarctic region - which are powerful and unique tools to study storms, substorms and M-I (magnetosphere-ionosphere) coupling processes. Using SuperDARN and large observational network in Antarctic region, the influence of current solar activity changes on storms, substorms and a variety of coupling processes in Earth's geospace environment should be investigated at this point by collaborating with in-situ satellite measurements (e.g., THEMIS, VAP, ERG) and theoretical researches.

How SuperDARN and NIPR Space and Upper Atmospheric Sciences Research Group can contribute to this particular important studies and what can be expected to be done will be discussed, and as a starting point of such researches, how polar cap sizes and cusp latitudes have behaved depending on the past solar cycle activities and under current solar activity will be studied and shown mainly using long term global SuperDARN observation data and influences of possible grand minimum will be discussed.

Occurrence characteristics of subauroral westward plasma flows and slowest limit of SAPS observed by the Hokkaido HF radar

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Westward rapid plasma flows in the ionosphere at subauroral latitudes are called Sub-Auroral Polarization Stream (SAPS) [Foster and Burke, 2002]. SAPS is a manifestation of the Magnetosphere-Ionosphere (M-I) coupling. Therefore, it is important to know occurrence characteristics of SAPS in order to understand the details of M-I coupling system. SAPS is affected by storms/substorms. As a result of the analysis of SAPS using the SuperDARN Hokkaido HF radar, Kataoka et al. [2009] reported that positions of SAPS shifts toward lower latitude with decreasing Dst index. However, there are questions which are not yet solved, such as quantitative effect of storms / substorms on SAPS and slowest speed limit of SAPS. We investigate the characteristics of SAPS, with focus on the relationship between occurrence characteristics of SAPS and a variety of solar wind and geomagnetic parameters, using the SuperDARN Hokkaido HF radar with a field of view covering Far East Russia, which has been in operation since 2006. In particular we identified the lowest limit of SAPS speed, which has not been discussed in the previous literatures. This is to identify the lowest threshold of electric field to generate SAPS as a result of M-I coupling. In order to investigate SAPS occurrence characteristics comprehensively, we analyzed events with wider ranges of velocity and MLAT than those in the previous studies. As a result of statistical analysis of SAPS, we found two categories of westward flows that were reasonably separated with a speed threshold of ˜150-200 m/s. For the faster flows above the threshold there is a clear correlation between MLAT and Dst index, whereas for the slower flows there is no such correlation. Similar correlation is found for MLT and AL index for two categories of westward flows. The faster flows are considered to be SAPS, whereas the slower flows are probably associated with midlatitude F-region ionospheric irregularities not directly related to storms / substorms. Furthermore, we have been investigating the phase dependence of substorms identified by AL index, which represents the most intense value of the Auroral Electrojet as determined by the high latitude geomagnetic field data.

Poynting vector measurements of whistler-mode chorus with THEMIS: Substructures within chorus source region?

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Whistler mode chorus is most intense electromagnetic waves observed in the terrestrial inner magnetosphere. The waves are observed mostly on the dawnside and are enhanced during geomagnetically disturbed periods. Chorus is observed in the typical frequency range from 0.2 to 0.8 fce with a gap at 0.5 fce, where fce is the electron gyrofrequency. The emissions below and above 0.5 fce are called lower-band and upper-band chorus, respectively. The Poynting vector measurements by various spacecraft directly showed that chorus is observed to propagate from the magnetic equator to higher latitudes, indicating that the waves are generated at the magnetic equator. We have investigated the propagation characteristics of lower-band and upper-band chorus emissions observed by THEMIS near the magnetic equator. Full measurements of wave electric and magnetic fields are used to estimate the Poynting vectors of both lower-band and upper-band chorus, and then their polar and azimuth angles respect to the ambient magnetic field are derived in this presentation, we report on events showing propagation direction deferences between lower-band and upper-band chorus at around the magnetic equator. During the events the lower-band and upper-band chorus are field aligned and have sufficiently larger wave amplitudes compared with those of reflected chorus waves previously reported, indicating that the waves are generated at around the magnetic equator. Our statistical investigation shows that such events are preferentially observed within 3 degrees from the magnetic equator, which indicates that the events are unique to the chorus source region. The events observed by the THEMIS spacecraft imply a possibility that apparent source regions of lower-band and upper-band chorus would be different, i.e., the source region of chorus is composed of two distinct subsets, one responsible for upper-band and one for lower-band chorus generation.

オーロラストリーマの移動に伴う磁気圏－電離圏結合対流の変動

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Variation of M-I coupling convection associated with auroral streamer

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To clarify Magnetosphere-Ionosphere coupling processes associated with auroral streamers, we developed a computer method that can explain interactions between Alfven waves and ionospheric convection. We also examined the variability of M-I coupling system associated with auroral streamers.

The current understanding about M-I coupling associated with auroral streamers is as follows. A bubble containing low plasma density is created by magnetic reconnection at the nightside magnetosphere. Then positive and negative charges show up at the flanks of this bubble. These charges create a dawn-dusk electric field in the same direction with ambient electric field and this accelerates the bubble. Groups of accelerated bubbles are called Bursty Bulk Flows(BBF). From both ends of BBF, Alfven waves are launched and generate a region-1 type current system. It is believed that auroral streamers are emitted when bubbles from the dusk side of BBF enter near-Earth region. Auroral streamers move equatorward on account of incident electric field from magnetosphere.

Although the cause of auroral streamers is regarded as BBF, there are some controversial points concerning the processes connecting the two. It is not clear how the polarization mechanism of BBF occurs, and how much BBF can intrude into the near-earth magnetosphere. Also, it is still uncertain how the ionosphere reacts to these BBF through magnetic field line. Furthermore, while auroral streamers are observed before or during substorm (ex. Nakamura et al, 1993, Nishimura et al, 2010), the connection between them is still open to question.

Under these circumstances, in this study, we carried out numerical simulation to examine how the ionospheric convection changes when auroral streamers penetrate the auroral region. In this simulation, we made a pair of FAC that corresponds to auroral streamers passing through the high conductivity region and examined the potential variation processes. As a result, we found that ionospheric potential structures were distorted significantly in the longitudinal direction when auroral streamers approached the auroral region. This is because Hall- polarization charges show up near the conductivity boundary. As the conductivity in the auroral region is high compared with the surrounding area, polarization of Hall current flowing along the equipotential lines of auroral streamers occurs. The new electric charges created by this process create new electric potential, which result in distorting the original potential structures. We cannot rule out the possibility that feedback effects occur from these polarization charges into the magnetosphere. In this study, we also calculated the variation of electric field and electric current associated with auroral streamers.

オーロラストリーマの磁気圏電離圏結合過程の解明を念頭に置いた、アルヴェーン波と電離圏対流の相互作用を記述するソルバーを開発し、ストリーマの移動に対応した結合系の変動特性についての考察を行った。

オーロラストリーマに関する磁気圏―電離圏結合の現在の解釈は以下の通りである。夜側磁気圏のリコネクションより生成された、周囲よりプラズマ密度の低いバブルが、地球方向へ加速されるとともに朝側・夕側でそれぞれ正・負の電荷をつくり、背景電場と同じ朝―夕方向の分極電場が生まれる。加速されたバブル、すなわち BBF は、その両端でアルフベン波を励起し、Region1 型の電流系を生み出す。BBF の夕側に対応する upward FAC 領域では、電子の降り込みによる発光領域オーロラがオーロラストリーマとして観測され、BBF から投影された分極電場とともに赤道方向へ駆動する。

以上のように、オーロラストリーマの成因は BBF であると推測されているが、両者をつなげるプロセスにおいて議論の分かれる部分も多い。BBF の分極のメカニズムや、地球近傍に侵入した BBF のその後の発達だけでなく、このような挙動により、磁力線を通して電離圏がどのように応答するかは明らかでない。また、サブストームオンセット直前や拡大相中にもオーロラストリーマが観測されるが（例えば、Nakamura et al, 1993, Nishimura et al, 2010）、オーロラストリーマとサブストームオンセットのつながりも未解明の部分が多い。

以上のような背景を踏まえ、本研究では、オーロラストリーマがオーロラ帯に侵入する際の電離圏対流の変化を調べる数値計算を行った。この計算では、電気伝導度を周囲より一様に高くしたオーロラ帯に、オーロラストリーマに対応する FAC を接近させ、その過程での電離圏ポテンシャルの変化を調べた。その結果、オーロラストリーマがオーロラ帯に侵入するときに、ポテンシャル構造が経度方向に著しく拡大することが確かめられた。この歪みは、境界付近に生まれた Hall 分極電荷によるものと考えられる。オーロラ帯の電気伝導度は周囲の領域に比べて高いために、オーロラストリーマがつくる等ポテンシャル線に沿って流れるホール電流の分極が起こる。そこで生じた分極電荷が、新たなポテンシャルを作り出し、本来のポテンシャル構造を変形させる原因だと推測できる。このように生じた分極電荷から、磁気圏側へ FAC としてフィードバックする効果も考えられる。本研究では、オーロラストリーマの移動に伴う電流・電場構造の変化も再現したので、その考察も行う。

パルセーティングオーロラとコーラス波動の周期性に対する地球磁場勾配の影響

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Effect of geomagnetic field gradient on periods of pulsating aurora and chorus waves.

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In order to understand generation of pulsating aurora (PA) and energetic electron dynamics, we have been observing simultaneously VLF emissions and PA on the ground at Athabasca (L=4.3) in Canada.

In this study, we have made a periodicity analysis for PA and chorus waves observed on 7 February 2013. The periodic variations of auroral luminosity and chorus intensity showed one-to-one correspondence.

In this event, when the periodic PA luminosity disappeared, the spectral characteristics of chorus waves changed from discrete rising-tone emissions to hiss-like emissions.

It is reported that the geomagnetic field gradient along a field line near the equatorial plane plays an important role in the appearance of hiss-like emissions. If the geomagnetic field gradient becomes more gradual, then a threshold amplitude for triggering the chorus emissions becomes smaller in a nonlinear theory of chorus generation. As a result, multiple chorus waves are readily generated, and hiss-like emissions are produced by a number of chorus waves merging with each other in their dynamic spectra.

For this event, we calculated geomagnetic field gradient variations along the field line near the equatorial plane by using the Tsyganenko 2004 model. They varied from 152.6 nT/Re at the time of chorus observation to 139.3 nT/Re at the time of hiss-like emission observation. It indicates that the geomagnetic field gradient became more gradual when the hiss-like emissions were observed. It is consistent with the generation process of hiss-like emissions based on the nonlinear theory.

This is an important ground observation result indicating that the geomagnetic field gradient along a field line near the equatorial plane affects the period of PA, and the generation process of hiss-like emissions.

We will present in detail the changes in the periodicity of PA and the spectral characteristics of chorus waves corresponding to the variation of the magnetic field gradient.

パルセーティングオーロラ（PA）の発生と高エネルギー粒子の動的な振る舞いを知るために、我々はカナダのアサバスカ（L 値＝ 4.3）にて PA と VLF エミッションの地上同時観測を行っている。

本研究では、2013 年 2 月 7 日に観測された PA の輝度値とコーラス波動の強度に対し周期性解析を行った。その結果、両者の周期性には 1 対 1 対応が見られた。

このイベントでは、ある時間に PA の輝度変化の周期性が失われ、同時にコーラス波動のスペクトル特性もライジングトーンコーラスエミッションからヒスライクエミッションへと変化した。

ヒスライクエミッションの生成には、磁気赤道付近の磁力線に沿った地球磁場勾配が重要な役割を有するという報告がされている。地球磁場勾配がより緩やかになることで、非線形成長理論に基づいたコーラス波動が発生するための振幅の閾値が低くなる。その結果、より多くのライジングトーンコーラスが生成され、これらがスペクトル上で重なりあうことでヒスライクエミッションが形成される。

本イベントにおいて、Tsyganeneko 2004 モデルを用いて地球磁場勾配を計算すると、152.6 nT/Re から 139.3nT/Re へと減少しており、ヒスライクエミッションの観測時に地球磁場勾配が緩やかになっていることが確認された。これは、非線形成長理論に基づいたヒスライクエミッションの生成プロセスと定性的に一致する結果である。

本研究は、磁気赤道付近の磁力線方向に沿った地球磁場勾配が PA の周期性とヒスライクエミッションの生成に影響を与えるということを示す、重要な地上観測結果と考えている。

本発表では、地球磁場勾配の変化に対応した、PA の周期性及びコーラス波動のスペクトル特性の変化について詳細に報告する。

耐放射線特性に優れたプラズマ波動観測用 ASIC プリアンプ

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Radiation hardened ASIC preamplifiers for plasma wave observations

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Plasma wave observations by miniaturized and multiple satellites in the magnetosphere are important to understand the magnetospheric dynamics. Further reductions in the mass, volume, and power of analog circuits are continually being made in scientific instruments designed for plasma wave observations. We have been studying the miniaturization of the plasma wave instruments without degrading the electrical performances by using an application specific integrated circuit (ASIC) technology. In our pervious study, ASIC preamplifiers for magnetic field measurements (1 Hz ˜100 kHz) were developed by using 0.25 um complementary metal-oxide semiconductor (CMOS) technology.

In this study, in order to considerably reduce circuit resources (mass, volume, and power) for analog component of plasma wave instruments, we have developed a new ASIC preamplifier for electric field measurements and a triangular wave oscillator for a calibration system. A voltage gain of 10dB, a bandwidth of several MHz, and low impedance (50 ohm) drive are necessary for an ASIC preamplifier for electric field measurements. In comparison with the ASIC preamplifier for magnetic field measurements, the ASIC preamplifier for electric field measurements is designed for wideband operation with an improved output buffer driving a low impedance load.

In addition, a calibration system is built with a triangular wave oscillator. A wide frequency response can be evaluated by a number of harmonics of the triangular wave. We can embed preamplifiers and an oscillator together within a one chip. This could contribute to further miniaturization of plasma wave receivers.

Finally, total ionizing dose (TID) effects cannot be ignored for observations in a space environment. We could mitigate the TID effects by using CMOS devices having a gate oxide film which is much thinner than used in the conventional product. We experimentally confirmed that our ASIC preamplifiers exposed to a TID level 100 krad did not increase in noise property. We could develop a radiation hardened ASIC preamplifiers.

We will present the design principles of our ASIC preamplifier for plasma wave observations and discuss its electrical performances in detail.

磁気圏でのプラズマ波動観測は小型衛星や複数衛星での多点観測が主流となりつつあり、電磁波観測器の小型化、軽量化、低消費電力化が求められている。そこで、我々はアナログ ASIC(特定用途向け回路) 技術を用いて電気特性を劣化させることなくプラズマ波動観測器の超小型化の検討を行っている。先行研究では昨年度までに 0.25um の CMOS デバイスを用い従来の衛星搭載用観測器と同等のノイズ性能をもつ交流磁界用 ASIC プリアンプ (数 Hz 〜100 kHz) を開発した。

本研究では、電磁波観測器のアナログコンポーネントに対して更なる小型化を狙い、交流電界用 ASIC プリアンプの開発と校正に用いる三角波発振器の開発をそれぞれ CMOS デバイスを用いて行った。電界観測用 ASIC プリアンプは電圧増幅率が最大で 10dB 程度、周波数帯域は数 MHz、低負荷 (50 オーム) の駆動を可能にする必要がある。そのため磁界観測用プリアンプと比べて、周波数帯域の広帯域化と最終段の負荷に流れる電流を増加させるように設計した。

また新たに校正システムとして三角波発振器の搭載を検討している。基本周波数を数百 Hz とする三角波を印加することにより、三角波が持つ高調波成分から広帯域の周波数特性が容易に得られるという特長を有する。三角波発振器を CMOS デバイスで実現することにより、1 チップ内にプリアンプと校正用発振器を同梱させることが可能になり、更なるシステムの小型化に寄与できる。

最後に、宇宙環境での自然波動観測において放射線の影響は無視できない。我々は民生品のものより十分にゲート酸化膜の薄い CMOS デバイスを用いて、ゲート酸化膜中の結晶欠陥に捕獲される正孔を低減させ、放射線の影響の改善を図った。開発した ASIC プリアンプと従来の衛星搭載用プリアンプに 100 krad のガンマ線を照射しそれぞれの電圧雑音の比較を行った。ASIC プリアンプはフリッカ雑音に対して影響が全くない結果が得られ、放射線に対して極めて強い耐性を実現した。

本発表では、我々の開発している交流電磁界用 ASIC プリアンプについての設計原理と実験結果について詳細に述べる。

Medium energy particle analysers for ERG: performances of engineering models and designs of flight models

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ERG (Exploration of energization and Radiation in Geospace) is a geospace exploration spacecraft, which is planned to be launched in FY2015. The mission goal is to understand the radiation belt dynamics especially during space storms. The key of this mission is the observations of electrons and ions in medium-energy range (10 – 200 keV), since these particles account for the significant portion of energy density in the radiation belt region, and also excite various electromagnetic waves (e.g., EMIC waves, magnetosonic waves, and whistler waves), which are believed to play significant roles in the relativistic electron acceleration and loss. Engineering models (EMs) of medium energy electron analyser and ion mass spectrometer have been developed and their performances are evaluated. The results are reflected in the design of the flight models.

カナダ・アサバスカで同時に観測されたVLF/ELF波動とパルセィティングオーロラの数十秒スケールでスイッチングする相関関係

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Tens of seconds switching of correlation between VLF/ELF chorus wavesand pulsating aurora observed at Athabasca, Canada

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We investigate dynamic switching of lag time between pulsating aurora intensity and chorus waves which were observed on 7 February 2013 at Athabasca in Canada (L=4.3), using a crossed-loop antenna and a narrow field-of-view EMCCD camera. Power spectra of pulsating auroral intensity and chorus wave intensity at 1.8-2.5 kHz show a same pulsation period at 0.1-0.15 Hz. Lag times between pulsating aurora intensity and chorus waves are evaluated by using a cross-correlation analysis. We found that two patterns of arrival time difference switches with a time scale of a few tens seconds. One pattern shows that electrons reached ionosphere later than the associated chorus waves with a delay time of 2 s, consistent with the theoretical value for south-going electrons reflected at the ionosphere in the southern hemisphere. The other pattern shows that electrons reached ionosphere earlier by 4.5 s than the associated chorus waves, consistent with the theoretical value for south-going chorus waves reflected at the ionosphere in the southern hemisphere. These results firstly show that interaction process of high-energy electrons and chorus waves are changing with a time scale of a few tens seconds.

私たちは、カナダ・アサバスカ観測点（磁気緯度 61.2 度、L=4.4）で、ループアンテナを用いて 100kHz サンプルの VLF/ELF 波動観測を 2012 年 9 月 25 日から行っている。2013 年 10 月からの冬期には狭視野の EMCCD カメラを設置して同時定常観測を行い、オーロラと VLF/ELF 波動の関係を調べている。本研究では、2013 年 2 月 7 日に観測されたパルセーティングオーロラとコーラス波動の間に見られた相関関係の時間変化について調べた。このパルセーティングオーロラの強度変化と 1.5-2.5 kHz のコーラス波動の強度変化のパワースペクトルを比較し、両者は 0.1-0.15 Hz の同じ脈動周期があることが分かった。これらの間の相互相関解析から、オーロラ粒子とコーラス波動の磁気圏赤道面から地上までの到達時間差を見積もった結果、2 つのパターンの時間差が数十秒スケールで切り替わっていることを見出した。1 つ目のパターンは、波動よりも電子の方が 2 秒遅く電離圏に到達していることを示しており、これは南向きに伝搬した電子が南側半球で反射した場合の理論値と一致する。2 つ目のパターンは、波動よりも電子の方が 4.5 秒早く電離圏に到達していることを示しており、これは南向きに伝搬した波動が南側半球で反射した場合の理論値と一致する。これらの結果は、高エネルギー電子とコーラス波動の相互作用が数十秒スケールで切り替わっていたことを初めて示すものである。

Dipolarization Frontの時間発展及びダイポール領域との相互作用に関するシミュレーション研究

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Time development of Dipolarization Front and its interactions with the dipole region obtained by full-particle simulation

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A front of bursty bulk flows with large B_z (northward component of the magnetic field) are generated by magnetic reconnection in the magnetotail, is called Dipolarization Front (DF). Under the picture of Near-Earth Neutral Line model, which is one of the models explaining the triggering mechanism and development of a substorm, compressions of the dipole region by DF and pileups of the magnetic fluxes carried by flows cause a considerable increase in B_z in the night-side magnetosphere. There are no full-particle simulations that examine the case in which DF approaches the dipole region, although there are a number observational studies of DF with spacecraft data.

In this study, we have performed a 2-1/2 dimensional full-particle simulation for the initial magnetic configuration akin to Earth's dipole magnetic field together with a stretched magnetic field by a thin current sheet. We have generated the magnetic reconnection and earthward plasma flows accompanied by B_z, and examined the time development of the front of the flow, i.e. DF, until it approaches the dipole-like region.

In the simulation, the B_z carried by the reconnection flow piles up slightly away from the dipole-like region because of the two dimensionality and periodic boundary condition. Time variations in several physical parameters (B_z, J_y: westward current, N: particle density) near the DF in the simulation show the similar features to observations by THEMIS probes [Runov et al., 2011]. We also compare time development of energy pitch angle distribution (PAD) to that of the observation. Energy fluxes near 0, 90, and 180 degrees of ion's PAD increase after the arrival of the DF in our simulation, whereas those of electron's PAD increase in the observation. This result indicates that Betatron and Fermi accelerations which cause the increase of electron's energy flux do not work in this simulation system. The ion's PAD calculated at an off-equatorial location shows the increase of energy flux near 0 and 180 degrees, and this character is also similar to that of electron in the observation.

地球磁気圏尾部での磁気リコネクションによって生じる北向き磁場成分B_zの増大を伴う Bursty Bulk Flow(BBF) の前面は Dipolarization Front(DF) と呼ばれる。DF によるダイポール領域の圧縮と、B_zを伴う BBF の pileup によって磁気圏夜側の Bz が広範囲にわたって増大し、サブストームトリガーモデルの 1 つである Near Earth Neutral Line モデルが説明される。人工衛星観測に基づいた DF に焦点を当てた研究は近年数多く報告されているものの、DF がダイポール領域付近に到達した場合の粒子シミュレーション研究は報告されていない。

本研究では、2-1/2 次元粒子シミュレーションの初期条件として地球ダイポール領域を模した磁場構造と尾部横断電流層の磁場構造をつなげた磁場構造を採用した。電流層の中心で磁気リコネクションを発生させ、B_zを伴う地球向きのプラズマ流の前面である DF が、ダイポール領域付近まで到達するまでの時間発展を調べた。

シミュレーションの空間 2 次元性と周期境界条件によって、ダイポール領域と DF の間でプラズマ流が停留し、DF に伴うB_zはダイポール領域から少し離れた位置に pileup した。また、磁気赤道面の特定の位置における複数の物理量 (B_z、J_y: 西向き電流、N:粒子密度) を THEMIS 衛星の観測結果 [Runov etal., 2011] と比較し、類似した時間変化を得た。さらに、DF が pileup した場所でのエネルギーピッチ角分布を観測と比較した。THEMIS 衛星観測では、電子について 0 度、90 度、180 度のフラックスが上昇した一方で、シミュレーションではイオンについて同様のフラックスの上昇が得られた。これは、実際の磁気圏で考えられるベータトロン加速とフェルミ加速による電子のエネルギーフラックスの上昇が、シミュレーションの系では成り立たないことを示唆している。シミュレーション内で磁気赤道面から少しはずれたところで求めたイオンのピッチ角分布は、0 度と 180 度のフラックス上昇を示し、こちらも観測の電子のピッチ角分布と同様の特徴を示した。