かぐやで観測されたオーロラキロメータ波の偏波観測とレイトレーシングによる解析

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Polarizations of auroral kilometric radiatin (AKR) observed by Kaguya and their ray tracing analyses

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In KAGUYA (SELENE) LRS instrument[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 with a more reliable method mainly 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，従来よりも偏波判定の確度を高めた方法により、両半球が見える状態で両偏波が観測された例を中心に、観測結果とレイトレーシングによる解釈を示す [3]。

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Relativistic Electron Precipitation and Acceleration by Parallel Propagating Whistler Chorus Waves: GEMSIS-RBW Simulations

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Whistler chorus wave has an important role to accelerate electrons to over a few MeV from hundreds of keV, as well as to precipitate relativistic electrons into the atmosphere. These electrons are scattered through electron cyclotron resonance process at not only a magnetic equator but also off-equatorial region. The scattering of electrons at off-equatorial region shows a nonlinear acceleration process through a phase trapping by a raising tone whistler chorus element propagating parallel to a magnetic field line. On the other hand, relativistic electrons with pitch angle close to the loss cone can also be scattered at the off-equatorial region, and be a cause of relativistic electron precipitation into the atmosphere through the pitch angle scattering.

This study shows a competitive process between relativistic electron acceleration and loss by whistler chorus waves, using the GEMSIS-RBW model. The RBW simulation calculates wave-particle interactions between whistler chorus waves and radiation belt electrons along a magnetic field line. Whistler chorus waves propagating at higher magnetic latitudes can precipitate electrons with higher kinetic energies. On the other hand, electrons with a few hundreds of keV can be accelerated into relativistic energies through the nonlinear phase trapping process. Discussion will focus on flux variation associated with the competitive process between the acceleration and loss. Influence of relativistic electron precipitation on the flux depletion will also be discussed.

Statistical analysis of plasmaspheric magnetosonic mode waves from Van Allen Probes observations

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Magnetosonic waves (MSWs) are electromagnetic emissions whose properites can be described by the cold plasma extraordinary mode, which are typically generated between the proton cyclotron frequency and the lower hybrid resonant frequency. It has been suggested that MSWs can contributed to the acceleration of relativistic electrons in the radiation belts. In this study, we investigate the Poynting vector of plasmaspheric MSWs using the spectral matrix data from the EMFISIS instrument onboard the Van Allen Probes spacecraft. Our Poynting vector analysis showed that the observed MSWs propagate azimuthally around the Earth, which have been suggested by previous ray tracing studies (Kasahara et al, 1994). We also identified MSWs propagate radially across the field line. In particular, the occurrence of MSWs propagating inward from higher L-shells increases during magnetically active periods. We investigated the polarization of MSWs derived from the spectral matrix using the SVD method (Santolik et al., 2003). We found that MSWs can be converted to the left-hand polarized EMIC waves when the frequency of MSWs becomes lower than the local cross-over frequency. We thus suggest that one of the origins of the plasmaspheric EMIC waves is the mode conversion from MSWs.

A statistical study of EMIC waves with frequency variations observed by THEMIS.

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Recent observations reported electromagnetic ion cyclotron (EMIC) triggered emissions with rising tones between the H^+ and He^+ cyclotron frequencies in the Earth's magnetosphere. These emissions can play an important role in magnetospheric dynamics and their global distribution has been of great interest.

We develop a program to identify whether EMIC emissions have frequency variations or not, and perform a statistical study of frequency variations of the EMIC waves, that occurred in the equatorial magnetosphere from L=5.7 to L=10 at all local times, using data from the THEMIS probes during 2013 and 2014. We calculate the sweep rate of EMIC emissions using power spectral density. Results show that rising or falling tones occur during over 30% of times when EMIC emissions were observed. The strong rising tones have high occurrence rate near the dayside magnetosphere where the solar wind dynamic pressure is high. In addition, the frequency sweep rate and growth rate of wave amplitude tend to increase as wave amplitude becomes large.

Observation strategy of the plasma wave experiment (PWE) onboard ERG

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The SPRINT-B/ERG satellite is a Japanese small satellite mission to investigate dynamics of the inner magnetosphere. To achieve comprehensive observations of plasma/particles, fields, and waves, the Plasma Wave Experiment (PWE) is installed onboard the ERG satellite to measure electric field in the frequency range from DC to 10 MHz, and magnetic field in the frequency range from a few Hz to 100 kHz. Two CPU boards, one for electric field and another for magnetic field, are installed for the PWE and the measured data by the PWE are processed by these CPUs. A variety of operational modes can be implemented without changing the hardware configuration, and the telemetry data consists of several kinds of data such as power spectrum, waveform and spectral matrix. Some of them are continuously generated 24 hours per day and are downloaded to the ground, while the other data such as waveform data are once stored in the mission data recorder (MDR) and partial data is downloaded after data selection process. Besides the PWE, the Software-Wave Particle Interaction Analyzer (S-WPIA) will be equipped onboard the ERG in order to realize direct measurements of wave-particle interactions, and it is necessary to take into account the co-operational data processing and data flow with the S-WPIA.

The development of the PWE is almost reaching its final phase, but we still have some action items to be solved in the software development. One of essential items is generation algorithm of the spectral matrix. In order to determine the absolute direction of the wave using spectral matrix, it is indispensable to calculate cross spectra between electric and magnetic wave fields but the CPUs are independently assigned to them so that we need to introduce some synchronization technique to overcome this problem. Another one is the optimization of the operational plan of the MDR. We intermittently generate waveform data, which is so-called 'EWO-burst mode' and tentatively store them in the MDR. We prepare two kinds of EWO-burst mode; one is 'chorus-burst' and another is 'EMIC-burst'. As we need to select them due to the limitation of telemetry resource, efficient data selection scheme is very important to obtain maximum science output using the reproduced EWO-burst data from the MDR. In addition, triggering logic for the EWO-burst will play an important role.

In the present paper, we introduce a current design of onboard software preferable for the PWE onboard ERG according to the scientific objects of the mission.

Effects of EMIC rising tone emissions on magnetospheric plasmas

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We perform self-consistent hybrid simulations on electromagnetic ion cyclotron (EMIC) triggered emissions with a gradient of the non-uniform ambient magnetic field and obtained broadband and clear rising tone EMIC emissions. We also performed the test particle simulations for scattering of the relativistic electrons. Broadband emissions induce rapid precipitation of energetic protons and relativistic electrons into the loss cone since the scattering by the concurrent triggering takes place faster than that of the coherent emissions. The coherent triggered emission causes efficient proton acceleration around the equator because of the stable particle trapping by the coherent rising tone emission. Nonlinear trapping causes significant relativistic electron scattering in wide energy range. Since the frequency of the rising tone emissions reaches close to the gyro-frequency and the emission also induces lower band EMIC waves which are also close to the gyro-frequency, the minimum resonance energy of the electrons reaches 300 keV. The higher energetic electrons (with 6 MeV to 20 MeV) are scattered almost 70 % for both broadband and rising tone cases. The hybrid simulations including cold ion heating are also performed, which shows the selective heating of heavy ions (Helium and Oxygen). These heating mechanism also makes the dynamic spectrum of the EMIC wave complex.

X線天文衛星「すざく」による太陽極大付近での木星X線の観測

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Suzaku observation of Jovian X-rays around solar maximum

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We report on Suzaku observation of Jupiter in 2014. Recently, Chandra, XMM-Newton, and Suzaku have discovered several X-ray emissions from Jupiter. Suzaku found diffuse X-ray emission associated with inner radiation belts thanks to its higher sensitivity in 1 - 5 keV (Ezoe et al. 2010). To understand a relation of this emission to the solar activity and its spectral properties furthermore, we conducted a new Suzaku observation in 2014. We found that the diffuse X-ray emission exists around Jupiter but its luminosity and spectrum seem to be changed from 2006. We discuss our results in the context of the solar activity and inner radiation belts.

本講演ではX線天文衛星「すざく」による2014年の木星観測の結果について報告する。近年、Chandra、XMM-Newton、「すざく」などの活躍により、太陽系天体からのX線放射が多数発見されている (Bhardwaj et al. 2007)。これら太陽系天体からのX線放射のメカニズムについては徐々に明らかになってきてはいるものの、他のX線天体と比べて“冷たい”天体であることからも、太陽系天体のX線研究は未解明な部分の多い研究分野である。木星は太陽系最大の惑星であり、高速の自転が生み出す磁場強度は木星表面で4ガウスと、地球の10倍ほどもある。さらには数百木星半径にも及ぶ巨大な磁気圏と、その内部6木星半径の位置に、衛星イオの火山ガスをプラズマ源とするイオプラズマトーラスをもつ。木星X線の放射領域、放射メカニズムについては先攻研究によりある程度分かっており、主に太陽活動との関係が議論されている。今回観測に用いた「すざく」は高感度かつ低バックグラウンド検出という特徴を持ち、2006年の「すざく」観測では、世界で初めて木星の周りの広がった放射を確認している (Ezoe et al 2010)。この広がった放射については現在、逆コンプトン放射であるとする議論があるものの、詳細は未解明のままである。広がった放射や太陽活動との関係など、未だ残る木星X線の謎の解明に向け、私たちは2006年の追観測として、太陽活動が活発である2014年に「すざく」による木星の観測を行った。

まず初めに、スペクトル解析の結果、今回のスペクトルは3つのガウシアン、制動放射、巾関数からなるモデルでよく再現できた。これらガウシアンの内2つは0.23、0.78 keVで、それぞれ炭素や硫黄、酸素の重イオンと木星大気との電荷交換反応による輝線放射と考えられる。制動放射の温度は0.45 +/- 0.02 keVであり、太陽コロナとよく一致する。さらにもう一つのガウシアンは1.32 keVであり、太陽コロナ由来のマグネシウムイオンの輝線と考えられることから、これらは木星表面における太陽X線の散乱を示唆する。また巾関数は、ベキが0.26 +/- 0.2と非常にフラットであり、非熱的放射を強く示唆する。モデルから見積もられるX線光度は0.2 - 1、1 - 5 keVでそれぞれ (1.6 +/- 0.4) x 10^{16}、(2.7 +/- 0.4) x 10^{15} ergs/secであった。

次にイメージ解析として、背景点源を除去した後、木星の静止座標系に直したイメージを作成した。0.2 - 1 keVのイメージでは木星本体からの点源状の放射を確認した。一方、1 - 5 keVのイメージでは、2006年と同様に、木星の周りに広がった放射の兆候が確認できた。イメージの輝度分布から、木星本体と広がった放射の割合を見積もると、これらのX線光度はそれぞれ (1.2 +/- 0.3) x 10^{15}、(1.5 +/- 0.3) x 10^{15} ergs/secと考えられた。

2006年と比べると、木星本体のX線光度は0.2 - 1 keVで4.4 +/- 1.2倍、1 - 5 keVで1.5 +/- 0.6倍に増大していることから、どちらも活発化した太陽活動を反映していると思われる。一方で、広がった放射のX線光度は0.60 +/- 0.17倍と少し暗くなっている。本講演では、広がった放射の起源について、これらのスペクトルおよびイメージ解析の詳細解析の結果を元に議論する。

Geotail衛星データを用いた昼間側磁気リコネクションの構造の解明

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Study of the dayside magnetic reconnection through the analysis of Geotail data

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In the present study, we have investigated the magnetic reconnection structure in the dayside magnetosphere that has not been studied intensively compared to that in the nightside, by analyzing the Geotail data. In the nightside magnetosphere (magnetotail), it is considered that a symmetric reconnection will occur because the characters of plasmas of two upsteram sides are almost the same. On the other hand, in the dayside magnetosphere (magnetopause), it is considered that the asymmetric reconnection will occur because the magnetospheric plasma and the solar wind plasma are both involved in the reconnection. It is considered that the nightside reconnection has a quadrupole structure produced by Hall effect, and the dayside reconnection has the dipole structure. We selected the reconnection events based on the simultaneous sign inversion of the ion flow velocity and the magnetic field from the Geotail data. We could select 34 cases in 1995-2014, and found that they have either quadrupole or dipole structure in the duskward magnetic field component (B_y). Further, we investigated the magnetic field structure near the neutral line by analyzing the changes in the ion density and the magnetic field when the Geotail passes near the neutral line. In 10 cases, they have the quadrupole structure in By, and the averaged value of the ion density ratio is 6.3 (Density in the magnetosheath / Density in the magnetopause). The averaged value of the magnetic field ratio is found to be 1.76 (B_z in the magnetopause /$|B_z|$in the magnetosheath). On the other hand, in 24 cases that have the dipole structure, the averaged value of ion density ratio is 17.3, and the averaged value of the magnetic field ratio is 2.54. These values are greater than those with quadrupole structure. In addition, in the cases of dipole structure, when the value of the ion density ratio is large, the change in B_y tends to be large. We will discuss the difference between the symmetric reconnection and the asymmetric reconnection based on these results.

本研究では、磁気圏夜側に比べ、これまで重点的に研究されてこなかった磁気圏昼間側の磁気リコネクション構造について GEOTAIL 衛星のデータを用いて調べた。一般的に、磁気圏夜側では磁場強度・密度・温度の等しい磁気圏プラズマ同士がリコネクションを起こすため対称な空間構造を持ったリコネクションが起ると考えられている。他方、磁気圏昼間側では磁気圏プラズマと太陽風プラズマがリコネクションを起こすため、非対称な構造を持ったものになると考えられている。また、磁気圏夜側のリコネクションでは Hall 効果に起因する四重極磁場構造がみられ、磁気圏昼間側のリコネクションでは双極子磁場構造がみられると考えられている。本研究では、GEOTAIL 衛星観測データをもとに速度と磁場の同時符号反転を基準にリコネクションイベントを選定した。1995～2014 年において選定したイベント数は 34 例で、それぞれのイベントの磁場構造には四重極構造あるいは双極子構造のいずれかがみられた。選定したイベントにおいて、衛星の磁気中性線通過前後のイオンの密度や磁場の大きさの変化量等を調べることにより、中性線付近の磁場構造について詳細に解析した。その結果、四重極構造がみられた 10 例のイベントの磁気中性線通過前後のイオンの密度比 (シース中の密度/磁気圏中の密度) の平均値は 6.3、磁場強度比 (磁気圏中の B_z/シース中の $|B_z|$) の平均値は 1.76 と小さかったのに対し、双極子構造がみられた 24 例のイベントではイオンの密度比の平均値は 17.3、磁場強度比の平均値は 2.54 と大きなものになった。また、双極子構造がみられたイベントにおいてイオンの密度比が大きいと、X ポイント付近の B_y の変化量が大きく、磁場構造に与える影響が大きいという結果も得られた。この結果をもとに、非対称磁気リコネクションについて議論する。

Van Allen Probes observations of dipolarization and its associated O+ flux variations in the inner magnetosphere

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Recent study employing the MDS-1 satellite reveals that magnetic field dipolarization in the deep inner magnetosphere is not unusual. When the MDS-1 satellite was located at L=3.5-5.0 near the auroral onset longitude (MLT difference of <2.5 h), the occurrence probability of local dipolarization was about 16%. Surprisingly, an event was found at L~3.6, far inside the geosynchronous altitude. It was also shown that after the dipolarization, the oxygen ENA flux in the nightside ring current region measured by the IMAGE satellite was predominantly enhanced by a factor of 2–5 and stayed at an enhanced level for more than 1 h, while clear enhancement was scarcely seen in the hydrogen ENA flux. To better understand mechanisms of the selective acceleration of O^+ ions during dipolarization, an in-situ measurement of ion fluxes is needed. However, there are few studies investigating H^+ and O^+ flux variations during dipolarization in the deep inner magnetosphere.

In this study we investigate magnetic field dipolarization and its associated ion flux variations in the deep inner magnetosphere, using magnetic field and ion flux data obtained by the Van Allen Probes. From the magnetic field data recorded on the nightside (1800-0600 MLT) in the inner magnetosphere (L=3.0-6.6) in VDH coordinates, we select substorm-related dipolarization events in which the H component increases by more than 20 nT and the absolute value of the V component decreases by more than 8 nT in 5 minutes. About 150 dipolarization events are identified from 1 October 2012 to 30 June 2015. We find that the dipolarization mostly occurs at L=4.5-6.5 in the premidnight sector (2100-0000 MLT). No events are found at L<4.0. Some dipolarization events are accompanied by O+ flux enhancements in the energy range higher than a few keV, which have the pitch angle distribution peaked around 45 or 135 degrees. We also find that low energy O^+ ions often appear after dipolarization with an energy dispersion starting from around keV down to a few tens of eV. These energy dispersive O^+ ions are detected in the directions parallel and antiparallel to the magnetic field line. We will discuss possible mechanisms of the selective acceleration of O^+ ions and the generation of the field-aligned sub-keV O^+ ions in the deep inner magnetosphere during the dipolarization events.

サブストーム開始前後に観測される高い電流密度

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High current density observations in the near-Earth plasma sheet before and after the substorm onset

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The statistical properties of the near-Earth current sheet from 8 Re to 12 Re were recently revealed by the THEMIS multi-spacecraft measurements [Saito, 2015]. A typical cross-tail current density in the near-Earth tail (X=-8 to -12 RE) was found to be ˜2 nA/mˆ2, while in some cases, the current density increased above 4 nA/mˆ2. High current density of the cross-tail current sheet in the near-Earth (X˜-10 RE) plasma sheet is a prominent signature during the growth phase of substorms. To understand where the tail energy is stored and released, temporal evolution of the current density was analyzed based on the THEMIS multi-point magnetic field data from 2007 to 2013. In the tail outside X˜-10 RE, the high current density was observed before the onset and decreased gradually during the expansion phase, being consistent with the previous studies. However, in the inner edge of the tail (X˜-8 RE), the current density was also high in quiet times. In addition to that it increased temporally after the onset for a few to several minutes. These high current density observations before and after the onset suggest that the tail energy is released outside X˜-10 RE and that new current system, which may be related to the aurora formation, is formed after the onset within X˜-8 RE.

Bi-modal log-normal distribution of substorm intensity: What does it mean?

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One of the essential issues in substorm study is how is the substorm intensity distributed and what determines the distribution. In this study, we made a data base of substorm onset and intensity for a long period from 2005 to 2014 by using Wp index provided by WDC for Geomag, Kyoto University and OMNI data base. Then, the substorm intensity (AL index) distribution is statistically studied using the data base. The obtained major results are,

1) Substorm intensity shows bi-modal log-normal distribution.

2) Its major peak is in small AL range around 100 nT and the secondary peak is around 300 nT.

3) The occurrence ratio between the major and second groups is 52%:48% (Number of small substorms is comparable with larger substorms).

4) The ratio of integrated AL value between the major and second groups is 32%:68% (One third of magnetospheric energy may be dissipated through small substorms) .

The major and secondary groups are considered to be pseudobreakups and full substorms, respectively. The bi-modal distribution of substorm intensity means that substorm is not a continuum state between pseudo-substorms and full substorms as has been discussed, and may suggest that two different substorm processes are working. What are the two different substorm processes? Do they imply the different solar wind-magnetosphere interaction process, two types of loading-unloading process, or different substorm triggering?

テミス衛星による多重サブストームの事例解析

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THEMIS satellite observations of a multiple-onset substorm

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A multiple-onset substorm with stepwise poleward expansions is studied. Five successive auroral brightenings were identified in all-sky images roughly every 10 minutes starting at 0213 UT on 27 February 2009. The first brightening was weak and the second brightening was the substorm initial brightening. Other brightenings expanded poleward thus were auroral breakups. The breakups occurred stepwise, i.e., later breakups initiated near the latitude where the previous poleward expansion has reached. Corresponding reconnection signatures are studied using THEMIS satellites observations between 8 and 24 Re down the tail. The initial brightening was not accompanied by clear reconnection signature at 8, 10, and 24 Re down the tail. On the other hand, subsequent three auroral breakups were simultaneous with three fast flows at 24 Re, thus are associated with reconnection. The three fast flows were a tailward flow and subsequent two earthward flows. The flow reversal simultaneous with the second breakup indicates that the tailward retreat of the reconnection site occurred in a stepwise manner, because another tailward retreat is expected at the third breakup. We interpret that the stepwise characteristic in the tailward retreat and poleward expansion is caused by possible stepwise magnetic flux pileup.

脈動オーロラにおける内部変調の起源について

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Origin of internal modulations of the pulsating aurora

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We investigate the origin of the internal modulations, so-called quasi-few Hz modulations of precipitating electrons for the pulsating aurora by comparative studies between the Reimei observation and a computer simulation for the chorus-wave particle interactions. From the Reimei observations, the main modulation of precipitation, with a few seconds, and the internal modulations, with a few Hz, that are embedded inside the main modulations are identified. A computer simulation that calculates interactions between the bouncing electrons along the magnetic field and the propagating whistler mode waves shows that the generation and collapse of the lower-band chorus bursts determines on-off switching of the pulsating aurora. A train of rising tone elements embedded in the lower-band chorus bursts drives the internal modulations. Besides the internal modulations, the Reimei satellite found a precipitation gap between intermittent precipitations above a few keV and stable precipitations around 1 keV. The gap corresponds to the half-gyro frequency gap between the lower-band chorus waves and the upper-band chorus waves.

2015年1月7日および3月18日の磁気嵐におけるリングカレントイオンの特徴

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Characteristics of ring current protons and oxygen ions during the 7 January 2015 and 17 March 2015 storms

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We investigate enhancements and losses of energetic (˜50-˜500 keV) protons and oxygen ions during two intense storms on January 7 and March 17 in 2015. We use proton and oxygen ion data from RBSPICE onboard Van Allen Probes.

During the January 7 storm (Dst_{min} = -99 nT), Van Allen Probes explored the inner magnetosphere on the night side, with both spacecraft located around midnight at apogee. Their orbits were in opposite phase. RBSPICE data are available from both spacecraft during the rapid recovery of the storm. We analyze energy spectra of both species to identify whether the ring current is symmetric or not, and determine the dominant loss process.

During the March 17 storm (Dst_{min} = -223 nT), Van Allen Probes traveled in the pre-midnight sector during the outbound paths and around midnight during the inbound path. The orbits of the two spacecraft were in opposite phase. The Dst index during the storm showed a two-step decrease with the first minimum at 9 UT and the second at 22 UT. Enhancements of ring current ions began at RBSPICE-B at ˜7 UT, and RBSPICE-A entered the ring current region at ˜9 UT. The RBSPICE data show penetration of energetic protons (mu˜0.1 keV/nT) down to L˜4 during the first storm development. Protons penetrated more deeply (as low as L˜3) during the second enhancement. The protons, which we confirmed made a dominant contribution to energy density at L = 3-4, are more enhanced in flux around the storm maximum. The flux of 200-400 keV oxygen ions was enhanced and localized around midnight near the end of the first storm development. Oxygen ion enhancements during the second development were seen in a wide range of MLT (pre-midnight to midnight). We examine the evolution of ion energy spectra to identify whether each phase of the multi-step storm development was due to deep penetration of transport/injections, density enhancements, or/and non-adiabatic acceleration of protons and oxygen ions.

オメガバンドオーロラの発生特性

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Growth signature of omega band auroras

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We examined omega band auroras observed with the THEMIS ground based all-sky imagers. Using 8 years data from 2007 we found a large number of events that showed almost whole processes of the generation of omega band aurora from the initial growth phase to the declining phase through expansion phase. The interesting features for the growth of omega band aurora are as follows; the omega band aurora grew from a faint seed, not via distortion of pre-existing east-west band aurora. The aurora did not show any shear motion during the growth of auroral activity. The omega band auroras occur in the post midnight to morning sector auroral zone during the recovery phase of magnetospheric substorms. They drifted eastward with a speed of a few hundred meter/sec. Ps6 magnetic pulsations with period of ˜10-30 minutes were observed in association with the occurrence of omega band aurora, most apparent for the Z component. A black hole-like dark aurora was found during growth and expansion phase just at the eastside of omega band aurora. Omega band aurora generally consists with intense pulsating aurora.

In this study we examine generation and growth signatures of omega band auroras with referring optical imager, particle and field observed onboard THEMIS spacecraft, and ionospheric convection obtained by SuperDARN radars.

およそ 8 年分の THEMIS 全天オーロラ画像ネットワーク観測データを用いてオメガバンドオーロラの特性を調べた。これまでの解析により、オメガバンドオーロラの生成期から拡大期、減衰期までの一連のライフサイクルついて数多くのイベント例を得ることができた。オメガバンドオーロラの成長特性として以下のことが明らかになった。オーロラは弱い種から次第に成長して、形状が大きく明瞭になってゆく。既存の東西方向のバンド状オーロラがねじ曲げられてオメガ状に形成されるのでは無い。成長過程では回転を伴う捻れ運動はほとんど起こらない。オメガバンドオーロラはオーロラサブストームの回復期の真夜中から朝側に出現し、およそ毎秒数百メートルの速度で東向にドリフトする。周期が 10 分から 30 分ほどの Ps6 地磁気脈動を伴い、特に Z 成分の振動が顕著である特性を有している。オメガバンドオーロラの生成・成長期の特性として、ほぼ全ての場合において、直径が数百キロメートルの円形の形状をしたブラックオーロラを東側に伴っている。ブラックオーロラ内の下向き電流とオメガバンドオーロラ内の上向き電流とがペアーとなって存在し、相互に強め合うことによりオメガバンドオーロラが成長しているようである。さらに、オメガバンドオーロラの微細構造として、強い脈度オーロラを伴っている場合がほとんどである。このような特性を有するオメガバンドオーロラの発生機構を明らかにするために、可視オーロラと Ps6 との詳細比較、衛星との同時観測、SuperDARN データとの比較などを行った。

惑星間空間磁場朝夕成分駆動シータオーロラにともなう単極性沿磁力線電流系の観測：1998年－2004年の組織的調査

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Observation of a unipolar FAC system associated with IMF By triggered theta auroras: A systematic survey for 1998-2004

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We investigate the existence of a specific field-aligned current (FAC) system predicted by numerical magnetohydrodynamic simulations in a past study. The FAC system is expected to occur when a drifting theta aurora is formed in response to a stepwise transition of interplanetary magnetic field (IMF) By during strongly northward IMF periods. The FAC system appears on the rear side of the drifting crossbar of the theta aurora, with its polarity controlled by IMF By. When the crossbar is drifting dawnward (duskward), the FACs flow into (away from) the ionosphere. The purpose of this paper is observational verification of the above-mentioned IMF By-controlled FAC system. In reality, however, the stepwise IMF By change as simulated is of vary rare occurrence. We systematically surveyed IMF data during the period of 1998-2004 and found four events of almost ideal By transitions. For the four events, five crossbar overpasses by Defense Meteorological Satellite Program (DMSP) satellites were available. For all five overpasses, the aforementioned FAC system was confirmed using precipitating particle, magnetic field, and ion drift data obtained by the spacecraft. Thus we conclude the real existence of the model-predicted FAC system associated with IMF By triggered theta auroras.

我々は、以前に数値電磁流体シミュレーションにより予見された、ある沿磁力線電流系の実在について調査する。強い北向き惑星間空間磁場（IMF）が続いているとき、IMF の朝夕成分（By）が階段状に変化すると、極冠内を朝夕方向にドリフトするシータオーロラが現れる。本研究が対象とする沿磁力線電流系はそのシータオーロラに付随して起こる。その出現場所は移動するシータオーロラの後方で、その極性は IMF By に制御されている。シータオーロラが朝側（夕側）に移動している場合は、沿磁力線電流は電離圏に流入する（電離圏から流出する）向きである。本論文の目的は、この IMF By が制御する沿磁力線電流系の観測的検証である。現実には、シミュレーションで用いられたような階段状の IMF By 変動が起こることは極めてまれである。我々は 1998 年から 2004 年の IMF データに対して組織的な調査を行い、IMF By が理想に近い階段状変化を示す 4 事象を見出した。その 4 事象において、Defense Meteorological Satellite Program (DMSP) 衛星がシータオーロラ上空を通過する観測が 5 個あった。その 5 観測全てにおいて、DMSP 衛星で得られる降下粒子データ・磁場データ・イオンドリフトデータを用いて、上述の沿磁力線電流系を確認できた。したがって、我々はシミュレーションで予測されたシータオーロラ付随沿磁力線電流系は実在すると結論する。

On the formation and origin of substorm growth phase/onset auroral arcs inferred from conjugate space-ground observations

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Magnetotail processes and structures related to substorm growth phase/onset auroral arcs remain poorly understood mostly due to the lack of adequate observations. In this study we make a comparison between ground-based optical measurements of the premidnight growth phase/onset arcs at subauroral latitudes and magnetically conjugate measurements made by the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) at ˜780 km in altitude and by the Van Allen Probe-B spacecraft crossing L values of ˜5.0-5.6 in the premidnight inner tail region. The conjugate observations offer a unique opportunity to examine the detailed features of the arc location relative to large-scale Birkeland currents and of the magnetospheric counterpart. The observations strongly suggest that the premidnight arc is connected to highly localized pressure gradients embedded in the near-tail R2 source region via a local upward FAC.

IMAP/VISIにより磁気嵐回復時に観測されたサブオーロラ帯発光現象

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Unusual emission in the sub-auroral region during the recovery phase of magnetic storm obtained with IMAP/VISI

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We report unusual emission event in the sub-auroral region obtained with IMAP/VISI occurred in the recovery phase of a big storm in July 2015. IMAP/VISI is a visible imaging spectrometer which aims to measures nightglow emissions from ISS (~400 km altitude) covering the wide range from +51 deg. to -50 deg. in geographical latitude. Two slits of VISI point to +45 deg. and -45 deg. to nadir to achieve a stereoscopic measurement of the airglow and aurora emission. In the nominal operation mode, VISI continuously measures emissions at O2 762 nm, OH or N2 1PG 730 nm and O 630 nm simultaneously with a spatial resolution (plate scale) of ~10 km x 14 km and scan width of ~600 km (mapped to the E-region altitude) perpendicular to the orbital track.

A big storm started on June 21, 2015 and Dst index decreased to 195 nT at 5UT on June. IMAP/VISI measured the dot- or tail-shaped emission in the evening sector of sub-auroral region in the southern hemisphere. The dot or tail structures were continuously measured in successive six orbits during the period from ~1645 UT on June 24 to ~0030 UT on June 25 in the recovery phase of the big storm. We found that the dot- or tail-shaped structure is most distinct in O 630 nm with intensities of a few hundreds Rayleighs, but it is also identified in O2 762 nm and OH/N2 1PG 730 nm. The size of spot or tail was approximately several tens to a few hundreds km. However, no background continuum emission was found associated with the structure. These spot or tail structures were obviously separated from the auroral oval emission with a typical latitudinal gap of ~10 deg. Comparing the VISI data between front FOV and rear FOV, the structure shapes are almost identical. This is the first time we identified these structures separately from the auroral oval since the launch in 2012.

From the facts mentioned above, we suggest that the emission cannot be attributed to city light, lightning fishing boats. It is probably difficult to explain the dot or tail structure by airglow process. It is likely to cause the spot- or tail-shaped emission by auroral precipitating electrons. To produce the emissions at O 630 nm, O2 762 nm and N2 1PG 730 nm simultaneously, electrons in the broadband energy range from low-energy to several keV should be required. In this talk we give the discussion on the mechanism for these structure and the relationship to SAR arc or SAPS.

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ダンジェー対流の誤り

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Misleading concept of Dungey convection

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Spectacular aurora behaviors observed at the substorm onset are surprising enough to make us believe that they are something unusual phenomena caused by extraordinary plasma processes such as explosion and instability. For the substorm as an abnormal phenomenon in plasma, understandings for individual processes such as growth phase, quiet arc, on set, dipolarization, WTS, and streamers are made uniquely for each process, and consequently mechanism for each process is consider almost independently. Typical examples that reflect these situations would be the NENL and the CW. What is lying on the base of these troubles is misleading concept of Dungey convection. An image that open magnetic fields pull magnetospheric plasma makes us understand the convection in a wrong way. A fatal error caused by such image is to underestimate the role of pressure regimes in the convection system. These misunderstandings have given rise to the substorm that excessively depends on the effect of NENL.

Recently, it has been found that finer the spacial resolution of the global M-I coupling simulation is, the more realistic features of the polar substorm are reproduced. While observed signatures of the polar substorm reveals the results of M-I coupling process, a serious difficulty of the substorm study is that even if the results are known it is not directly connected to clarify the cause of the substorm. The most significant difficulty is to know how and to where perturbation observed in the polar substorm are projected along magnetic field line or current line to the magnetospheric structure. It is what known as the projection problem. Although satellite observations were expected to solve this problem, the solution was not obtained due to the weakness that the whole M-I structure cannot be known from the satellite observation. Even from the satellite observations, the understanding for the substorm process was done only by connecting symbolized mechanisms like the NENL and the CW. Projection problem is still the most critical issue for the substorm research.

The results of simulation can solve the projection problem. Results of substorm reproduction in MHD seems to indicate that the substorm is the development and transition of the convection system. In the substorm process based on the development and transition of the convection system, all disturbances from the growth phase to the expansion phase are understood as a successive series of mutually related phenomena. Convection must intend to form a self-consistent structure among magnetic field, flow, FAC, energy conversion, and the shear formation. Although the substorm is a non-steady-state, the self-consistent structure must be held even during the substorm. In the estimation process based on the observation, it tends to consider only parts neglecting the self-consistency over the whole system. This is probably the reason why the substorm elements are considered almost independently to each other.

サブストームオンセットでは驚異的なオーロラ変動が観察される。これを見たら何か異常な現象であるという印象を受け、爆発、不安定などを連想するのはごく自然です。このようなプラズマ中の異常現象としてのサブストームでは、growth phase、quiet arc、オンセット、双極子化、WTS、ストリーマーなどの変動に対する理解に、それぞれの独自性が強く、おのおのに対してほぼ独立したメカニズムが考えられています。これらを色濃く反映する典型が、NENL と CW でしょう。そしてそれらの根底にはダンジェー対流という誤った概念が横たわっています。開磁場がプラズマを引っ張るというイメージが、対流を誤って理解させます。これによって圧力領域の生成を過小評価してしまうことが致命的です。これらのことが NENL の役割への過大依存を生んでいます。

最近のグローバル M-I 結合シミュレーションで、シミュレーションの解像度を上げると、極域サブストームの詳細が MHD で再現されることが分かってきました。そもそも極域サブストームは磁気圏ー電離圏系変動の結果を示すものですが、結果が判ってもそれが原因に直結しないところがサブストーム研究の困難です。最大の不確定要素は、極域で観測される磁場・プラズマ変動が磁気圏のどの構造に対応するか、すなわち投影問題です。衛星観測はこれを解決すると思われていましたが、全体は見えないという弱点のため、NENL や CW のような象徴化された変動の繋ぎ合わせでサブストームを理解するに終わっています。投影問題は依然としてサブストーム研究の最重要課題です。

シミュレーションの結果は、投影問題を解決できます。MHD での極域サブストームの再現は、サブストームが対流の変動と遷移であることを示しているように思われます。対流の変動と遷移に基づくサブストームの理解では、成長相から拡大相までが、一連の変動として説明されます。対流は、磁場、フロー、FAC、エネルギー変換、シアー形成が一体となって、自己無撞着構造を形成するものです。サブストームは、非定常ではあっても、この自己無撞着構造は保持されなければならなりません。観測からの推定ではどうしても部分だけを考えてしまい、全体の自己無撞着性を満たすことをおろそかにされます。これがおのおのが独立現象に近いサブストームエレメントを考えてしまう理由でしょう。

南IMF時のヌル-セパレータ構造とダンジェーサイクル

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The null-separator structure and the Dungey cycle in the southward IMF condition

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””The null-separator structure””

The solar wind-magnetosphere interface has a peculiar magnetic field configuration named by the null-separator structure [Watanabe et al., 2005]. In this structure, all magnetic fields in the solar wind merging with those in the magnetosphere pass the null points. In addition, there appears the special magnetic field line connecting two null points on which the solar wind (IMF), the open and the closed magnetic field lines meet. This field line is called the separator line [Stern, 1973]. The null-separator structure is well recognized in the global MHD simulation result for the northern IMF condition [Tanaka, 2007]. We can identify two null points in the nightside higher latitude region to the cusp in both hemispheres and two separator lines running in the dayside and in the nightside. However, this simple null-separator structure is not conserved in the southward IMF condition [Tanaka, 2007]. Tanaka (2007) reported the structure with the cusp-null, the X-null, and the separator line in the dayside magnetopause. This structure is different from that in the northward IMF condition. Therefore, the null-separator structure in the southward IMF condition is still an issue to be solved.

””The Dungey cycle””

The Dungey cycle refers to the convective motion of plasmas and magnetic field lines invoked by the merging in the dayside and that in the nightside in the solar wind-magnetosphere-ionosphere system. Namely, the magnetic field lines merging with the IMF in the dayside magnetopause are transported to the nightside magnetosphere and return to the dayside after reconnection in the nightside magnetosphere [Dungey, 1961]. This idea explains the ionospheric convection in the high-latitude ionosphere. As the Dungey cycle is regarded to be driven by merging in the dayside magnetopause, this cycle is regarded to be closely related to the null-separator structure. However, there are not so many studies about the Dungey cycle in terms of the null-separator structure. For example, Fujita et al. (2015) manifested driving mechanism of the Dungey cycle only in the dayside magnetosphere. Nobody study the three dimensional Dungey cycle in terms of the null-separator structure. The present study is the first one dealing with the Dungey cycle in the null-separator structure in the southern IMF condition by using the global MHD simulation.

””The three-dimensional Dungey cycle in the null-separator structure””

At first, we discuss transform of the null point when the IMF turns southward from northward. It is noted that the null points in the northward IMF condition are determined as two points in the northern and southern hemispheres. When the front of the IMF change (northward ->southward) in the solar wind arrives at the null point, there appears an additional, new null point which is transported along with the solar wind. The magnetic field intensity becomes very small along trace of the new null point. Probably, this trace is a null line between the original null point and the new null point although the numerical simulation with finite grid size cannot exactly reproduce the null line. In addition, this line is identical with the X-null found by Tanaka (2007). This line plays an important role in the three dimensional Dungey cycle in the southward IMF condition because the nightside reconnection of the Dungey cycle appears on this ””null line””. It is noted that the nightside second reconnection necessary for the Dungey cycle is apparently corresponding to the NENL [Baker et al., 1995].

Baker, D. N. et al. (1996), J. Geophys. Res., 101(A6), doi:10.1029/95JA03753.
Fujita, S. (2015), submitted to JGR
Stern, D. P. (1973), J. Geophys. Res., 78(31), doi:10.1029/JA078i031p07292.
Tanaka T. (2007), Space Sci Rev, DOI 10.1007/s11214-007-9168-4.
Watanabe, M. et al (2005), J. Geophys. Res., 110, A06210, doi:10.1029/2004JA010832.

MHD simulation of multiple x-line magnetic reconnection in the dayside magnetopause

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The spontaneous fast reconnection evolution is studied in asymmetric magnetic field configuration. In particularly, the multiple x-line reconnections are investigated in association with the presence of sheath flow using two dimensional MHD simulations. According to the fast reconnection development, the diffusion region extends in the direction of reconnection outflow. Then, secondary reconnection occurs to divide the diffusion region, and the magnetic reconnections in the secondary x-lines drastically evolve again. The sheath flow makes extending of diffusion region easy and cause the differences of reconnection rate at each x-line.

Comparison of global MHD simulations of sudden impulses with SuperDARN observations

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A set of global MHD simulations of the magnetosphere-ionosphere (M-I) coupled system have been performed to examine the IMF-By dependence of ionospheric convection variations associated with sudden impulses. The previous study on the IMF-By dependence but using SuperDARN (SD) radar observations showed that the higher-latitude portion of induced flow vortices has a dawn-dusk asymmetry in speed for negative SIs and its polarity of flow asymmetry flips depending on the IMF-By polarity. It was suggested that temporal evolution of the round convection cell due to variations of IMF-By generates this flow asymmetry. To study such an M-I coupled response to varying IMF-By from a theoretical point of view, we conducted global MHD simulations with increasing/fixed/decreasing IMF-By intensity associated with SIs. As a result, the simulation runs for negative SIs have basically reproduced the dawn-dusk asymmetry of the higher-latitude flows showing the same dependence on IMF-By intensity and polarity as seen by the SD observations. As also expected, the round cell strengthens in the case of increasing IMF-By as compared with the fixed and decreasing cases. A detailed examination, however, indicates that the evolution of the round cell upon solar wind pressure changes seems to be more complicated than expected. For example, the round cell always intensifies from the pre-SI level for negative SIs, while it weakens systematically for positive SIs, regardless of the change of IMF-By intensity. This result suggests that not only the IMF-By intensity but also some upstream conditions associated with solar wind pressure changes can contribute to the evolution of round cell. Therefore, the observed flows with a dawn-dusk asymmetry could result from the interplay of these two effects.

サブストーム開始時におけるグローバル磁場トポロジー変遷

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Transition of Global Magnetospheric Topology at Substorm Onset

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Recent magnetohydrodynamic (MHD) simulations indicate that the magnetic field topology of the magnetosphere is basically described by a torus representing the open-closed filed line boundary and a cylinder representing the open-interplanetary field line boundary. The torus is inscribed in the cylinder with a tangent topologically equivalent to a circle. The circle consists of two separators (which are also field lines) connecting two magnetic nulls on the circle. The torus surface consists of two separatrices, namely the separatrix northward of the separator circle and the separatrix southward of the separator circle. Similarly, the cylinder surface is divided into two separatrices by the separator circle. We call such structure of the magnetosphere the null-separator topology. When the interplanetary magnetic field (IMF) is northward, the null-separator topology almost always persists. For southward IMF, however, the null-separator topology is locally modified, sometimes drastically, although the global null-separator topology is basically retained. In this paper, we investigate the magnetic topology change at the onset of substorms simulated by global MHD modeling. In our simulation, a nonzero dawn-dusk component of the IMF was included in the upstream conditions. We found the following. Just before the onset, at x = -20 ˜-30 Re on the nightside, the torus surface northward of the separator circle and the torus surface southward of the separator circle are in contact with each other and reconnect. As a result, unconnected (IMF) lines produced by reconnection pierce the closed field line region, making another hole on the torus (i.e., a 2-fold torus or a double torus). We discuss how the 2-fold torus is formed at the substorm onset by analyzing the simulation data in detail.

低緯度朝側昼夜境界付近で観測されるPi2型地磁気脈動と湾型磁場変動

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[1] 九大・理・地惑; [2] なし; [3] 九大・イクセイ; [4] なし; [5] NICT

Pi2 pulsation and magnetic bay in low latitudes observed around the dawn terminator

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We examined Pi2 pulsations and magnetic bay observed simultaneously at low-latitude stations around the dawn terminator. We obtained the following results about Pi2 pulsations around dawn terminator [Imajo et al, 2015, JGR]:

(1) In the sunlit region, Pi2 oscillations tend to be polarized in the D (positive eastward) direction. (2) The D component oscillations in the dark and sunlit regions are in antiphase, whereas the H (positive northward) component oscillates in phase. (3) The D component oscillations in the sunlit Northern and Southern Hemispheres are in antiphase. (4) A statistical analysis indicates that these D component phase reversals occur about 0.5 hour sunward of the dawn terminator at 100 km in altitude, corresponding to the highly conducting E layer.

These results indicate that D component Pi2s in the dawn sector are controlled by the longitudinal gradient of ionospheric conductivities at the dawn terminator. We also investigated D component magnetic bays accompanied with Pi2 around the dawn terminator. We found both cases that the sense of the D component bay was reversed / not reversed with respect to the dawn terminator when the phase of D component Pi2 was reversed. This suggests that the sunrise effect on the Pi2 pulsation and the magnetic bay are not always same.

Reference: Imajo, S., et al. (2015), Pi2 pulsations observed around the dawn terminator, J. Geophys. Res. Space Physics, 120, 2088-8211;2098, doi:10.1002/2013JA019691.

複数衛星を用いた内部磁気圏で観測される low-m ULF 波の経度方向の広がり

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Azimuthal extent of low-m ULF waves in the inner magnetosphere observed by multiple satellites

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The azimuthal wavenumbers of Ultra Low Frequency (ULF) waves in the Pc3-5 frequency band (2-100 mHz), which can provide information about the azimuthal scale and propagation direction of a wave, are useful diagnostics of the waves generation mechanism. Low-m (m <10) waves are predominantly toroidal modes resulting from field-line resonances generated by an incoming fast mode arriving from the outer boundary of the magnetosphere. Several statistical studies, which present the distribution of ULF waves in the inner magnetosphere, have been performed using measurements from satellite [Zhu and Kivelson 1991; Anderson et al., 1990; Lessard 1999]. Using the magnetic field data from the CRRES satellite, Hudson et al. [2004] found that there is a comparable probability of occurrence of toroidal mode oscillations on the dawn and dusk sides of the magnetosphere inside geosynchronous orbit. Although previous studies have presented the spatial distributions of ULF power and occurrence in the inner magnetosphere, the spatial features of azimuthal wavelength in the inner magnetosphere are still incompletely understood.

We investigate the azimuthal extent of low-m ULF waves observed in the inner magnetosphere, using magnetic field data from the multiple satellites, including GOES 13, 15 and Van Allen Probes. We focus on a Pc5 pulsation occurring at 6:00-8:00 UT on 13 September 2014 during a storm recovery phase. These Pc5 pulsations are dominated by a 3 mHz toroidal component and large amplitude of 30 nT when the Van Allen Probes were located in the morning side (MLT˜5) at L˜6. Estimating m number from the phase difference of Pc5 pulsations and azimuthal separation between Van Allen Probes A and B, we find m =3 with westward propagation. These oscillations are not observed in the premidnight sector at L˜6.6 by the GOES 15 satellite while GOES 13 observes 3 mHz Pc5 pulsations in the postmidnight sector. These results indicate that these low-m Pc5 pulsations are not global in azimuth while the m numbers indicate that the azimuthal wavelength of ULF waves is large. In this presentation, we will show several events and discuss the generation mechanisms of ULF waves occurring in the inner magnetosphere with various m numbers.

Evolution and propagation of electric fields during magnetic impulses based on multi-point observations

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Sudden commencements (SCs) are one of the abrupt magnetospheric disturbance phenomena. They are triggered by a compression of the dayside magnetosphere, leading to fast mode wave propagation in the equatorial plane. On the other hand, the compression induces Alfven waves that propagate toward the polar ionosphere along magnetic field lines, and then ionospheric electric fields propagate toward low-latitude ionosphere at speed of light. Each propagation process is individually supported by MHD simulations and ground magnetic field data. Several direct observations have also provided evidence of the fast mode or Alfven wave propagation, but spatial and temporal evolutions of these propagations are not well known. For the latter process, a previous study using the Cluster satellites shows that upward Poynting fluxes transport electromagnetic energy toward the nightside magnetosphere. However, whether such upward Poynting fluxes are launched from the ionosphere or converted from fast mode waves has not been confirmed yet.

Motivated by these issues, we investigate evolution of the electric field in the magnetosphere-ionosphere coupled system using multiple satellites and ground-based observations during SCs. We use magnetospheric electric and magnetic field obtained by THEMIS (5 probes), Van Allen Probes (2 probes). Magnetometer data from GOES 13 and 15 are also used. We also obtain the ionospheric electric field data from SuperDARN (high latitude) and HF Doppler (mid latitude) radars. SC events are identified by the SYM-H index provided in the OMNI database and geomagnetic field data. The event selection criteria are set as follows: (1) SCs occurred from January 2013 to December 2014. (2) The amplitude of the SYM-H is more than 10 nT, and its rise time is less than 5 min. (3) A Preliminary Impulse (PI) is recorded in geomagnetic field data at the subauroral region.

Seventeen SC events satisfying these conditions show that the magnetospheric electric field responds within 1 s to the magnetospheric magnetic field. These events also show the time delay of the onsets between dayside and nightside magnetospheric electric fields. For example, we find a clear SC signature on March 17, 2013. The SC onset time of the dawnside electric field (~4.8 h LT, L~4) is 20 s later than the dayside one (~10.4 h LT, L~7). The nightside electric field (~1.0 h LT, L~5.5) starts to decrease after 35 s of the SC onset of the dawnside electric field. These propagation times can be explained by the fast mode wave propagation in the equatorial plane. At the midnight sector, however, the magnetospheric electric field responds simultaneously independent of the L-value. In addition, the SC onset of the nightside electric field (~21 h LT) is 15 s later than that of the midnight one although they are detected in the same L-value, which suggests that there may be a dawn-dusk asymmetry of the electromagnetic energy propagation time in the inner magnetosphere. In the ionosphere, both SuperDARN and HF Doppler radars detect a westward electric field at ~15 h LT about 1 min after the onset of the dayside magnetospheric electric field, which is consistent with the Alfven velocity from the dayside magnetosphere to the polar ionosphere.

We will clarify the spatial evolution of both fast mode and Alfven waves by statistical studies, and evaluate the possible propagation path of the electromagnetic energy associated with SCs to the ionosphere and inner magnetosphere.

Observation by SuperDARN Hokkaido East radar of a possible SC-triggered wave event including FLR

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In the sea/ground backscattered data obtained by the SuperDARN Hokkaido East radar, we have found a relatively short-lived (lasting for about an hour) wave event which could be classified as a different type from the typical long-lasting (several hours) waves frequently observed in the sea/ground backscattered data of SuperDARN radars. Our wave event is likely to have been triggered by an SC which took place around 09:50UT on Aug 19, 2009. The event also included an interval during which the wave amplitude and phase showed the typical pattern of the Field-Line Resonance (FLR); this is the first time this pattern has been identified in the sea/ground backscatterd data of the SuperDARN Hokkaido East radar.

The Harang Reversal: A New Interpretation based on the Magnetotail Stability

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If the transport of plasma-sheet ions is adiabatic and the magnetotail is in a steady state, it is expected, under a certain assumption, that the entropy parameter pVg increases and decreases along the convection flow in the regions corresponding to downward and upward field-aligned currents (FACs), respectively. This requirement, along with the condition for the interchange stability imposes an important constraint on the direction of the convection flow especially for downward FACs. It is deduced that for the dusk cell the convection flow in the downward R2 current has to be directed azimuthally duskward, which follows the sunward, possibly deflected dawnward, convection in the region of the premidnight upward R1 current. This duskward turn of the convection flow takes place in the vicinity of the R1-R2 demarcation, and it presumably corresponds to the Harang reversal. For the dawn cell the convection flow in the postmidnight downward R1 current has to significantly deflect dawnward, and then it proceeds sunward in the upward R2 current. Those interrelationships between the convection and FACs are verified with a quasi-steady plasma sheet configuration and convection reproduced by a modified Rice Convection model with local force balance. Using equi-potential contours as a reference, it is also suggested that auroral arcs mapped to the equator are oriented in the east-west and Sun-Earth direction if they are located in the premidnight R2 and R1 currents, respectively.

Harang discontinuity and ionospheric polarization field by Hall current divergence

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The ionospheric electric potential shows global asymmetries and localized structures. Whereas these structures have been mainly discussed as the projection of magnetospheric convection (or the distribution of driving source, FACs, generated in the solar wind-magnetosphere system), we have proposed that it is also possible to explain them purely by ionospheric polarization effects due to conductivity inhomogeneities. Our study has been based on a part of the M-I coupling theory [e.g., Yoshikawa et al, 2013a,b] including the idea of Pedersen/Hall divergence/polarization effect [e.g., Yoshikawa et al., JpGU, 2009]. Although the possibility of ionospheric effect had been reported [Wolf, 1970; Atkinson and Hutchison, 1978; Tanaka, 2001; Ridley et al., 2004], we have for the first time shown and addressed correctly the underlying physics.

By applying a simplified version of 'Hall conjugate method [Yoshikawa et al., JpGU, 2008]' to a 2D ionospheric potential solver, we separate the total field (Phi, ionospheric total potential) into the primary field (Phi_0, including the background and Pedersen polarization field) and secondary field (Phi_{Hall}, the polarization field generated by Hall current divergence).

In the previous meetings [Nakamizo et al., SGEPSS, 2012-2014], we have specified one-to-one correspondence between characteristic spatial gradients of conductivity and characteristic deformations of potential, as follows; (a) For simplicity we consider dawn-dusk symmetric R1-FAC as the driving source. As the reference field, we calculate the potential with the uniform conductivity distribution. This reference field is symmetric with respect to both the noon-midnight and dawn-dusk axes. From this condition we gradually add spatial structures on the conductivity distribution. (b) Equatorward conductivity gradient generates positive/negative Hall polarization field ($\mathrm{Phi}_{Hall,eq}$) around pre-noon/pre-midnight sectors. As the result the total field (Phi) rotates clockwise. (c) Day-night conductivity difference not only shifts the potential centers toward night due to Pedersen polarization effect (in other words, current continuity), but also generates Hall polarization fields ($\mathrm{Phi}_{Hall,te}$) along day-night terminators due to sharp conductivity gradients there, resulting in the convex/concave of total field (Phi) along terminators. (d) Auroral conductivity enhancement generates Hall polarization fields ($\mathrm{Phi}_{Hall,ao}$) around edges of conductivity band. Thus in the total field (Phi) a conspicuous structure appears around the midnight oval, resembling 'Harang discontinuity.'

This presentation gives a detailed analysis of point (d). Interesting point here is that we get Harang-like structure with simplified distribution of FAC, dawn-dusk symmetric R1-FAC, noted above. We will discuss the result in relation to the characteristics of 2D solver (perfect current confinement condition) and the advanced M-I coupling theory [Yoshikawa et al., 2013a,b].

(B,V)パラダイムで俯瞰する磁気圏電離圏結合

吉川 顕正 [1]
[1] なし

(B,V) paradigm of Magnetosphere-Ionosphere Coupling

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Global magnetosphere-ionosphere (M-I) coupling dynamics has been studied in the context how (B,V) paradigm magnetospheric dynamics interacts to the (J,E) paradigm ionospheric electrodynamics. In this scheme, the ionosphere is often treated as an electrostatic and/or incompressible medium hence the ionosphere instantaneously responses to the magnetospheric disturbances not only at the interface region where shear of geomagnetic field is directly mapping from the magnetosphere (e.g., polar ionosphere) but also at the region far from the M-I interface region (e.g., equatorial ionosphere). This means that causality and physics for vertical and horizontal propagation mechanism of ionospheric dynamics are neglected from the M-I coupling scheme. In this study we reconsider the M-I coupling process described by the (B,V) paradigm of ionospheric dynamics in the context of Hall-MHD. We will demonstrate about how dynamical process of Cowling channel formation and "transmission process of electric field" can be explained by the (B,V) paradigm.

Relationships of the transversely accelerated ions with auroral electrons and field-aligned currents in the Reimei observations

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http://www.stelab.nagoya-u.ac.jp/~hirahara/

After the launch in August, 2005, the Reimei satellite has been observing numerous types of the polar ionospheric plasma signatures especially during three winter seasons in the nightside northern polar region. It should be noted that the angular coverages of the plasma particle instrument on Reimei were sufficient for the northern hemisphere observations to investigate the detailed pitch-angle distributions influenced by the satellite velocity for the low-energy heavy ion measurements. Although the altitudes of the Reimei observations were not as low as the orbits of the previous satellite missions like DE-1, the Reimei high-time resolution data obtained from almost three-year operation of both ion and electron instruments could provide us with new insights into what kinds of properties of the plasma conditions at the low-altitudes initiate/control so-called transversely accelerated ion events often found in the auroral oval crossings. The successive measurements by Reimei are useful for studying this type of the ionospheric ion accelerations in the direction perpendicular to local magnetic fields due to the interaction with plasma waves even when the ion mass discrimination could not be done with the Reimei plasma instruments and neither electric field nor plasma wave observations are performed,

The survey of the Reimei ion and electron energy-time spectrograms indicates that it is quite rate to observe the TAIs with their uppermost energies up to 100 eV in largely developed inverted-V electron signatures correspondent to the intense upward field-aligned current regions, while the high-flux or high-energy (more than 1 keV in some cases) TAIs have frequently been found particularly in the poleward edge of the auroral oval. The preliminary comparisons between the TAIs inside/outside the electron inverted-Vs and the field-aligned current distributions show that the most intense and energetic TAIs tend to occur in the strong downward field-aligned current regions on the poleward side not on the inside of but adjacent to the large-scale inverted-Vs and auroral forms in the equatorward. These relationships imply that the high-flux/energy electron precipitations like the inverted-V events are not preferable for the high-flux/energy TAIs. It is also likely that time variations of the energy inputs like the sharply field-aligned precipitating electron (so-called Alfvenic electron) fluxes and/or the field-aligned currents into a fixed area affect the energization and flux of the ionospheric ions while remarkable electron signatures are not always associated with the intense/energetic TAIs. These observational facts mean that in-situ measurements by a single satellite would be insufficient because the time variations of the source energy inputs could not be addressed only with one satellite passing through the interesting region.

In this paper, we present the Reimei observations for discussing the TAIs and their relations with the energetic electron signatures and the field-aligned currents and propose the necessity to realize a space exploration mission using comprehensive and integrated measurements of plasma particles/waves and electric/magnetic fields with formation flight techniques for 2 - 4 compact satellites for extending these Reimei achievements.

Canada, Finland, 昭和基地のELF/VLF波動同時観測データの初期解析結果

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Simultaneous observations of ELF/VLF emissions at Canada, Finland, and Syowa Station - Initial results

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Previous researches show whistler mode emissions in the ELF/VLF range accelerate relativistic electrons in the inner magnetosphere. However, the global simultaneous distribution of ELF/VLF emissions has not been well understood. We investigate global simultaneous distribution of ELF/VLF emissions by analyzing the data obtained at 2 longitudinally-separated stations in the Northern Hemisphere and 1 station in the Southern Hemisphere in the auroral and subauroral latitudes, i.e., Athabasca, Canada (54.7N, 113.3W, magnetic latitude (MLAT): 61.3N), Kannuslehto, Finland (67.7N, 26.3E MLAT: 64.4N) and Syowa Station, Antarctica (69.0S, 39.6E, MLAT: 70.5S). Simultaneous data at these three stations are available during December 10-14, 2012, January 9-19 and January 29-February 4, 2013, and February 26-March 21, 2014 (total 47 days). As an example, we found intense hiss emissions with frequencies expanding from below 1 kHz to over 2.5 kHz started at 1240 UT at Athabasca, 1236 UT at Kannuslehto, and 1235 UT at Syowa Station during the recovery phase of a weak geomagnetic storm on January 18, 2013. A geomagnetic substorm was not observed at this time in the AE index, while the ACE satellite shows clear enhancement of solar wind density and solar wind speed by ~20 /cm^3 and ~40 km/s, respectively. The IMF-Bz was mostly northward during this interval. These results suggest that the ELF/VLF emissions is generated in the inner magnetosphere on global scale at the same time associated with drastic enhancement of solar wind density without substorms. In this presentation, we report initial result of these simultaneous observations of ELF/VLF emissions at 3 stations.

これまでの研究により、ELF/VLF帯のホイッスラーモード波は内部磁気圏における放射線帯電子の加速が寄与していることが分かっているが、離れた地点での同時観測による地球規模での空間的拡がりはよく分かっていない。本研究は、北半球のオーロラ帯からサブオーロラ帯にかけて経度方向に離れた2地点と南半球のオーロラ帯の1地点での同時観測データを用いることにより、ELF/VLF波がどれぐらいの経度拡がりをもって発生しているのかについて調べる。

本研究ではカナダのAthabasca（地理緯度:北緯54.7度、西経113.3度、 磁気緯度: 北緯61.3度）、フィンランドのKannuslehto（北緯67.7度、西経26.3度 磁気緯度:北緯64.4度）、南極大陸の昭和基地（南緯69．0度、東経39.6度、磁気緯度:南緯70.5度）の3地点におけるELF/VLF波動の同時観測を報告する。３ヶ所の同時観測データが存在するのは、2012年12月10日-14日、2013年1月9日-19日、29日-2月4日、2014年2月26日-3月21日の期間（合計47日）である。1つの例として、2013年1月18日に、Athabasca、Kannuslehto、昭和基地のそれぞれの観測地点において、Athabascaでは1240UTから、Kannuslehtoでは1236UTから、昭和基地では1235UTから時間とともに周波数が高周波まで拡がるhissが観測された。AE指数とDst指数から、この時間帯は弱い磁気嵐の回復相であるが、サブストームは生じていないことが分かった。一方で、ACE衛星の観測データからは、IMF-Bzが北向きを保ったまま、太陽風密度、太陽風速度が1210UTから20 /cm^3 、40 km/sほどの急激な上昇をしていることが分かった。これらの結果から、サブストームではなく太陽風密度の急激な上昇に伴って、内部磁気圏において地球規模で同時にVLF波動が発生した可能性が示唆される。本講演では、この例を含めて、3地点同時のVLF波動観測を調べた初期結果を報告する。

磁気嵐回復相における放射線帯電子加速過程のエネルギー依存性とコーラス放射の波動特性との関連について

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The relation between energy dependent enhancement of radiation belt electron and wave property of chorus during recovery phase

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By analyzing in situ observation results by Van Allen Probes, we study the spatial and temporal evolution of the phase space density (PSD) of radiation belt electrons, the plasma environment, and plasma wave activities in the Earth's inner magnetosphere during geomagnetic storms.

Radiation belts are the regions where relativistic particles are trapped by Earth's magnetic field. In general, the flux of outer radiation belt electrons decreases during the main phase of geomagnetic storms, while the flux variations during the recovery phase are observed differently in each storm [Reeves et al., 2003].

In the present study, we analyze the variation of radiation belt electrons during the recovery phase. We use the flux of relativistic electrons measured by the Relativistic Electron-Proton Telescope (REPT) [Baker et al., 2012] and Magnetic Electron Ion Spectrometer (MagEIS)[Blake 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]. The second invariant K and the third invariant L∗used in the present study are provided by the ECT Science Operations Center.

First, we analyze the radial distribution of PSD for particles of different first adiabatic invariants during the storm event. As a result, we identify magnetic storms that the PSD of relativistic electrons in the whole range of first adiabatic invariant =150˜5500 MeV/G simultaneously and magnetic storms that firstly the PSD of relativistic electrons of first adiabatic invariant less than 600 MeV/G increases in the early recovery phase and secondly relativistic electrons of first adiabatic invariant greater than 600 MeV/G increases in the late recovery phase. To understand the acceleration process occurring in these magnetic storms in detail, we analyze the occurrence status and the spectral characteristics of whistler-mode chorus during the event. In the result of the analysis, we find that whistler-mode chorus typically has two types of the spectral characteristic; one is intermittent rising-tones and another is continuous banded spectra. We discuss the result of the correspondence between the PSD enhancements and the plasma wave activities, particularly focusing on the spectral fine structures of chorus emissions.

本研究は Van Allen Probes 衛星によるその場観測結果に基づいて、磁気嵐時における放射線帯電子の位相空間密度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。放射線帯外帯電子フラックスは磁気嵐の発生により大きく変動し、磁気嵐の主相においてフラックスは減少することが明らかとなっている。その一方で、回復相でのフラックスの変動に関しては、磁気嵐前より増大する場合、減少する場合、あるいは磁気嵐前と同程度まで回復する場合など、磁気嵐によって異なる様相を示すことが明らかとなっている [Reeves et al., 2003]。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非断熱加速過程によると考えられている。非断熱加速過程を担うプラズマ波動としては、特にホイッスラーモード・コーラス放射が重要な役割を果たすと考えられている。

本研究では、磁気嵐回復相における放射線帯電子の変動を議論する。解析には Van Allen Probes 衛星に搭載された Relativistic Electron-Proton Telescope(REPT) [Baker et al., 2012] と Magnetic Electron Ion Spectrometer(MagEIS)[Blake et al., 2012] による電子フラックス、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、そして位相空間密度の解析に用いる第二断熱不変量 K と第三断熱不変量 L∗は ECT の Science Operation Center で提供されている値を用いた。まず、解析対象とした期間における位相空間密度の動径方向分布について、異なる第一断熱不変量 (μ) ごとに解析を行った。その結果、位相空間密度の μ ごとの変化において、μ =150˜5500MeV/G でほぼ同時に増加が確認される磁気嵐と、回復相初期に 1 MeV 程度 ($\mu \leqq$ 600 MeV/G) の粒子の位相空間密度が増加し、回復相の中盤から 2 MeV 以上の粒子の位相空間密度に顕著な変動が見出される磁気嵐

が確認された。
　それぞれの磁気嵐における増加過程を理解するために、イベント発生時のコーラス放射の発生状況ならびにスペクトル微細構造について解析を行った。その結果、解析対象とした周波数帯に見られるコーラス放射の典型的なスペクトルとしては、ライジングトーンの構造を持つ場合と、バンド状の放射となる場合の２種類が確認された。また、放射線帯電子が増加する時間帯にコーラス放射が強く励起されている様相が確認された。本発表ではさらに、コーラス放射のスペクトル微細構造の解析結果を示し、放射線帯電子加速過程との対応について議論する。

宮城県大崎市鳴子川渡で観測された14-20Hzの磁場変動

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Narrowband magnetic fluctuations at 14-20 Hz observed at Kawatabi, Miyagi

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Narrowband magnetic fluctuations in the frequency range of 14Hz - 20 Hz were detected by an induction magnetometer in Kawatabi, northwest of Miyagi prefecture, Japan. There was temporal variation of the frequency, with several Hz/hour. The bandwidth was typically less than 0.4 Hz. The magnetic fluctuations appeared mainly in the noon, during magnetically quiet period withKpindex of 0 - 3.

東北工業大学では，1997年よりインダクション型磁力計を用いたELF帯の地磁気変動観測を開始し，人工的なノイズの少ない宮城県大崎市鳴子川渡に磁力計を移動した1998年12月10日から現在まで，欠測はあるものの観測を継続している。観測周波数帯はおよそ0.125Hzから40Hz程度である。この周波数帯には，7Hz,14Hz,21Hz付近に常にシューマン共振が見られるほか，0.2-5Hz付近にIPDPを含むPc1，また，観測周波数帯全域にわたって，現地の雷による非常に強いノイズが観測される。

今般，これまで知られていた現象とは異なる狭帯域の磁場変動が，主に14Hzから20Hzの周波数帯に発見されたが，その成因がまだわかっていない。観測周波数はシューマン共振に近いが，シューマン共振よりはるかに狭いバンド幅(0.4Hz以下)のくっきりしたスペクトルを示し，重畳していても容易に見分けることができる。現地の昼の時間を中心に現れ，1時間に数Hz周波数帯が変化していく。継続時間は3時間程度のことが多いが，朝方20Hz付近に現れ，昼11時頃から1時間ほどで10Hzまで徐々に下がり，夕方から夜にかけてまた20Hzに戻る場合も見られた。時間的に連続して見えるスペクトルを拡大してみると，時間変化する短時間のスペクトルが次々連なっていることがわかる。現在見つかっている例は12月から2月にかけての冬季のものが多いが，9月の例もある。発生時のKp指数は0から3がほとんどで，地磁気が静穏な時期に観測されていたと言える。

磁場に平行・反平行方向に伝播するアルフヴェン波動群による粒子加速

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Acceleration of charged particles by parallel and anti-parallel propagating Alfven waves

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Large amplitude Alfven waves are ubiquitous in space. It is an interesting and fundamental question how charged particles are accelerated by non-monochromatic Alfven waves. The accelerated particles may play essential roles in various energetic space plasma phenomena including the diffusive shock acceleration (DSA).

In this study, we calculate particle motion in a presence of parallel and anti-parallel propagating Alfven waves. Recent study [1] revealed that such a combination of Alfven waves can trap the particles inside the ponderomotive potential well created by beating of the waves, leading to an efficient perpendicular acceleration. The limit of acceleration is determined by wave parameters. Furthermore, the distribution of the accelerated particles becomes power-law.

We extend this study using a group of waves both for the parallel and the anti-parallel propagating waves. Statistics of the particle acceleration is evaluated, as functions of various wave parameters such as the amplitude, number of waves involved, and the phase coherence among the waves. The acceleration limit and the acceleration time scale are evaluated also. Results will be considered from the viewpoint of providing seed particles for the DSA.

[1] Matsukiyo and Hada, Astrophys. J., 692, 1004-1012, 2009.

宇宙プラズマ中には大振幅の Alfven 波が普遍的に存在している。Alfven 波は多くの場合単色ではなく、多くの波動の集合とみなせるので、これらの波動群によりどのような粒子加速が生じるかは基礎物理過程として興味のある課題である。また、これらの粒子加速が衝撃波統計過程のための種粒子供給など、いくつかの物理過程において本質的な役割を果たしている可能性がある。

本研究では、背景磁場に対し平行方向に伝播する波動群と、反平行方向に伝播する波動群が存在する場合の粒子加速について考えた。先攻研究により、平行および反平行伝播する単色 Alfven 波の重ね合わせ場の中では、波動のエンベロープに捕捉された粒子が高効率で加速されること、波動の振幅、波数、周波数により加速限界が決まること、加速された粒子の分布はベキ型となることが指摘されている [1]。この研究を発展させ、我々は平行および反平行波動群の中での粒子加速に対して詳細な議論を行っている。通常の速度空間拡散過程とは異なり、バリスティックな加速（超拡散）が起こる。波動の振幅、モード数、位相相関などをパラメータとして、粒子加速の統計的性質、加速限界、タイムスケールなどについて解析し、さらに衝撃波統計加速の種粒子供給の観点から加速の有用性について言及する。

[1] Matsukiyo and Hada, Astrophys. J., 692, 1004-1012, 2009.

Radiation belt electron precipitation induced by large amplitude EMIC rising-tone emissions

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We study dynamics of radiation belt electrons interacting with large amplitude EMIC rising-tone emissions by performing test particle simulations. *Engebretson et al.* [JGR, 2015] reported observation of large amplitude EMIC rising-tone emissions outside the plasmasphere and depletion of radiation belt electrons in response to these emissions. We make the two kinds of wave models; one is in low-density region based on the observation and the other is in the plasmasphere. To reproduce the large wave amplitude we include the convective wave growth, which are neglected through propagation of EMIC model waves in the previous studies [*Omura and Zhao,* JGR, 2012, 2013; *Kubota et al.,* JGR, 2015]. Furthermore, we also include Landau damping in setting up the model waves. Comparing with a wave model ignoring the convective wave growth, it is found that the large wave amplitude contributes to rapid electron precipitation. Some of relativistic electrons change their equatorial pitch angles more than 15 degrees in a time scale of 0.1 s, precipitated into the atmosphere. We set up the EMIC model waves in a local longitude and distribute test electrons throughout all longitudinal direction initially. The electrons moving eastward encounter the localized EMIC waves and some of resonant electrons are precipitated into the atmosphere. We obtain distribution of radiation belt electrons with respect to their equatorial pitch angle and kinetic energy. We find that the frequency variation expands the resonant electron range of pitch angles and energies. For comparison with observation of precipitated electrons, we monitor fluxes of electrons lost into the atmosphere in a narrow longitudinal range. Furthermore, we find echo of electron depletion due to eastward drift around the Earth. Energy ranges of efficient precipitation are different depending on the regions of interaction inside and outside of the plasmapause. Inside the plasmapause, electrons with energy higher than 0.5 MeV are precipitated. Outside the plasmapause, on the other hand, only highly relativistic electrons with energy higher than 3 MeV are precipitated.

Cold heavy ion composition in the deep plasmasphere estimated from ion cyclotron whistlers observed by the Van Allen Probes

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Ion cyclotron whistlers are electromagnetic ion cyclotron (EMIC) wave generated by mode conversion from R-mode lightning whistler waves. Their propagation processes strongly depend on the dispersion relationship of EMIC. In our previous study, we statistically studied ion cyclotron whistlers observed by the Akebono satellite around L=2-4. We found that various species of cold ions (e.g. H^+, M/Q=2 ion, He^+, M/Q=8 ion, O^+, and heavier ion than O^+) affect to the generation and propagation processes of ion cyclotron whistlers. We examined spatial distributions of such cold ions by analyzing observed ion cyclotron whistlers.

In this study, we examine a spatial occurrence distribution and characteristic frequency variation of ion cyclotron whistlers observed by the EMFISIS instrument onboard the Van Allen Probe A. The EMFISIS instrument measures waveforms of full components of electric and magnetic fields. We analyzed the waveform data obtained by the EMFISIS-WFR during 16 months, and detected over 3000 H^+ band ion cyclotron whistlers at L inside 2. We found that the normalized crossover frequencies of observed ion cyclotron whistlers are around 0.8 at about 600 km altitude and they decrease with altitude. Under the simple cold plasma approximation, crossover frequency of H^+ band EMIC strongly depends on the local heavy ion composition. This result seems to reflect realistic heavy ion density gradient around the Earth.

Survey of large amplitude whistler mode waves in the inner magnetosphere: RBSP EFW observations

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Recent spacecraft observations have revealed existence of very large amplitude whistler mode waves in the radiation belt, which are characterized by their wave amplitudes exceeding 200 mV/m [Cattell et al., 2008; Cully et al., 2008]. Compared with gradual acceleration by repeated interactions with small amplitude (< 1 mV/m) waves, electrons may be abruptly accelerated up to MeV energy range by relatively few interactions with the large amplitude waves [Cattell et al., 2008]. At large amplitude, nonlinear aspects on wave-particle interactions are important and electrons can be accelerated up to relativistic energy through phase trapping [e.g., Omura et al., 2007]. Multi-satellite observations showed a possible connection between large amplitude whistler mode waves and bursty precipitations of relativistic electrons [Kersten et al., 2011]. Thus, very large amplitude whistler mode waves may play an important role in the radiation belt dynamics and survey of properties of the waves is important. We investigated statistically electric field data of the plasma waves provided by the EFW instrument [Wygant et al., 2013] onboard the RBSP spacecraft. We used the average and peak wave amplitudes in seven logarithmically spaced frequency bands from 0.8 Hz to 6.5 kHz at a cadence of 8 samples/sec (filter bank data). We will show distribution and occurrence of large amplitude whistler mode waves using the filter bank data and will discuss impact of the waves on the radiation belt dynamics.

Study of the magnetic storm phase dependence of the inner boundary of the plasma sheet electrons

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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 toward 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 is formed at a geocentric distance around 3 - 7 R_E. The location of the inner boundary of the plasma sheet particles has been investigated as an indicator of the evolution of the plasma sheet particles, part of which causes ring current in the inner magnetosphere. 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 used in this study are obtained by Electrostatic Analyzer (ESA) 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, 1 to 10 keV electrons measured by ESA was analyzed. First, we check a correlation between the position of inner edge and Dst index. In addition, the events in which we identified inner edge of the plasma sheet electrons are categorized into four groups : Type A (inner edges were identified when Dst $<$-30 nT during main phase), Type B (Dst $>$-30 nT during main phase), Type C (Dst $<$-30 nT during recovery phase) and Type D (Dst $>$-30 nT during recovery phase).

The result of the statistical study shows that the positions of the inner edge of the plasma sheet electrons depend on not only Dst index but also the magnetic storm phase. Comparing Type A with Type C and Type B with Type D, we find in the main phase of the magnetic storm that the identified inner boundaries of the plasma sheet electrons with energy of 1 keV and 9 keV are located around the similar radial distance. On the other hand, in the recovery phase of the magnetic storm, we find that the inner boundaries of the low energy electrons (˜1 keV) is closer to the earth than that of the high energy electron (˜9 keV).

Finally, we compared the locations of the inner edge of the plasma sheet electrons obtained by ESA onboard THEMIS satellite with those estimated based on the steady state drift boundary model using Volland-Stern electric field as proposed by Jiang et al. [2011]. We could confirm that the steady state drift boundary model is a good approximation in the main phase of the magnetic storm. On the other hand, we found that the model does not agree with the position of the plasma sheet electrons in the recovery phase of the magnetic storm. The disagreement is clearer for 1-keV electrons than for 10-keV electrons. So, the test particle simulation including the evolution of electric field will be need in order to confirm how the location of plasma sheet electrons varies in the storm time inner magnetosphere.

惑星間空間衝撃波到来時における内部磁気圏イオンダイナミクスのエネルギー、ピッチ角依存性

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Energy and pitch angle dependence of impact of interplanetary shock on ions in the inner magnetosphere

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http://space.rish.kyoto-u.ac.jp/people/2014/hiroki_tsuji/index-j.html

Cluster satellite observations have shown that, soon after arrival of the interplanetary (IP) shock, overall intensity of trapped ions rapidly increases and multiple energy dispersion appears in an energy-time spectrogram of ions with small equatorial pitch angles [Zong et al., 2012]. This is because IP shock redistributes the charged particles trapped in the inner magnetosphere and has a large impact on magnetosphereic ions. However, the acceleration and transport of ions with all pitch angles is not well understood. In order to investigate the impact on the trapped ions and its dependence on the pitch angle, we have performed test particle simulation under the electric and magnetic fields provided by the magnetohydrodynamics (MHD) simulation. In MHD simulation, we changed the solar wind speed (372 to 500 km/s) in order to reproduce the IP shock. The number density in the solar wind was set to a constant to be 5 cm-3, and the Z component of the interplanetary magnetic field (IMF) was turned from +5 to -5 nT. A fast mode wave propagates tailward in the magnetosphere just after arrival shock. The amplitude of the electric field exceeds 20 mV/m. To reconstruct an energy-time spectrogram of the oxygen ions at (7,0,0) Re in the GSM coordinates, we started to trace trajectories of ions the backward in time starting at (7,0,0) Re just after arrival of the fast mode wave.

Knowing initial and final positions in 6D space, we mapped phase space density f by using Liouvilles theorem.

The phase space density f before the arrival shock is assumed to be isotropic Maxwellian. The result shows that a multiple energy-time dispersion appears in the simulated spectrogram of the ions with small equatorial pitch angles. However, the multiple energy-time dispersion is not present in the spectrogram of the ions with equatorial pitch angle of 90 deg. The result of our simulation is consistent with the Cluster satellite observations. There are two types of the acceleration process. One is drift betatron acceleration, and the other is gyro betatron acceleration. We will discuss the acceleration process that generates the multiple dispersion effectively.

極冠オーロラの運動メカニズム再考: 2台の全天カメラと短波レーダーによる観測

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Motion of a transpolar sun-aligned arc: Simultaneous observations with two ASIs and HF radars

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Polar cap arcs have frequently been observed in the high-latitude ionosphere during northward interplanetary magnetic field (IMF) conditions. Polar cap arcs extending along the Sun-Earth line are sometimes called Sun-aligned arcs (SAA). It was statistically indicated that SAA move either duskward or dawnward depending on the sign of the IMF By. Milan et al. (2005) reasonably explained the motion of SAA as viewed from the IMAGE satellite, especially its dependence on the IMF By, by using a model based on magnetic flux transport by the ionospheric convection during northward IMF conditions. However, the spatial resolution and sensitivity of the space-based FUV images were insufficient for evaluating the model in detail. To further test the model, it is necessary to combine highly sensitive ground-based all-sky optical observations from more than two stations.

In this study, we evaluate and/or improve the model of Milan et al. (2005) by investigating large-scale imaging of SAA with two ASIs, one at Resolute Bay (RSB) in Canada (74.7 N, 265.0 E, 82.9MLAT) and the other at Longyearbyen (LYR) in Norway (78.1 N, 15.5 E, 75.3 MLAT). On January 12, 2013, a transpolar SAA was observed to move duskward during 30 min interval from 0800 to 0830 UT. The SAA was extending across the fields-of-view of the two ASIs and its sunward end was clearly connected to the auroral oval near noon. Since the model of Milan et al. (2005) assumes that there is a gap between the dayside oval and the sunward end of SAA, it is not able to explain the current observations. To further analyze this event, IMF data from the ACE satellite and ionospheric convection data from HF radars of SuperDARN were employed. Based on this simultaneous measurement, we propose a model which employs magnetic reconnection in the southern hemisphere to create open flux in the polar cap and push the SAA duskward. This new model is able to account for the motion of SAA connected to the auroral oval on the dayside.

極冠オーロラは，惑星間空間磁場 (IMF) が北向きのとき，磁気緯度 75 度以上の高緯度地域で頻繁に観測される現象である．極冠オーロラの中でも太陽方向に伸びた構造を持つものを特に Sun-aligned arc (SAA) と呼び，IMF By 成分の正負に依存して朝夕方向に運動することが統計的に示されている．その運動メカニズムは北向き IMF 時の極域電離圏対流に伴う開いた磁力線の輸送モデルによって説明されてきたが (Milan et al., 2005)，モデル考案の際に用いられた光学データは衛星による極端紫外線観測によるものであり，空間分解能や感度に限界があった．Milan らのモデルで提案されている運動メカニズムは SAA の構造的特徴と密接に関連するため，地上からの高感度観測による構造の輪郭把握が重要となるが，これまでの研究では，単一地点からの地上観測が用いられてきたため，観測視野の制限により SAA の全体像を把握することが困難であった．このことから，SAA の運動モデルを検証するためには，複数地点からの広域光学観測によってその全体像を把握することが必要不可欠であることが分かる．

本研究では，カナダ・レゾリュートベイ (RSB) 及び，ノルウェー・ロングイヤービエン (LYR) に設置されている 2 台の高感度全天イメージャを用いた 630.0 nm 波長の広域光学観測により，Milan らによる SAA 運動モデルと実際の観測データとの整合性を検証する．2013 年 1 月 12 日 0700 - 0830 UT に，朝側から夕方側へと移動する SAA が 2 台の全天カメラによって同時に観測され， この SAA が，RSB と LYR の双方の全天カメラの視野にまたがる巨大な構造を持つこと，さらに昼側でオーロラオーバルと接続されていることが明らかとなった．Milan らの運動モデルは昼側オーロラオーバルと接続されていないことが前提であるため，今回観測された SAA を説明することができない．この SAA の運動を説明するため，この時間帯における ACE 衛星による IMF のデータ，SuperDARN による極域電離圏対流のデータを用いた解析を行った．朝側高緯度領域の対流と IMF の状況を考慮し，南半球において，朝側領域に分布する閉じた磁力線と北向き IMF が起こす磁気リコネクションに基づいた SAA の運動モデルを提案する．このモデルにより，昼側でオーバルと接続された SAA の運動が説明可能となる．

サブオーロラ帯における地磁気脈動と対応した脈動オーロラとコーラス波動の地上観測

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Ground-based observations of pulsating aurora and chorus emissions corresponding to the magnetic pulsation in sub-auroral region

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Pulsating auroras (PA) are caused by quasi-periodic precipitation of high-energy electrons (several keV ˜tens of keV) through cyclotron resonance with whistler-mode waves near the magnetic equator. The physical mechanism of the repetition period of PA is still open. Previous studies reported two types of PA : one is the repetition period of PA related with latitudes and the other is not related with latitudes.

In this study, we have analyzed repetition periods of chorus emissions and PA associated with latitudinal variations. Chorus emissions and PA were observed at Athabasca in Canada (L value:4.3, Magnetic latitude:61.2 deg.), a using VLF loop antenna (100 kHz sampling) and an all-sky EMCCD camera (110Hz sampling).

We observed southward-drifting PA at 10:00-10:30 UT on 17 February 2015. The repetition period of PA was gradually shortened from 15 sec to 8 sec. At the same time chorus emissions having a good correlation with PA were observed, and its frequency gradually rose with the southward-drifting PA. The frequency of chorus emissions is proportional to the gyro frequency in the generation region. The rising frequency would suggest that an equatorial source region of chorus emissions moves inward to the earth.

We calculated a bounce period of energetic electrons (1 keV ˜100 keV) by using Tsyganenko 2002 model. For each energy, the calculation result of bounce period difference is less than 1 sec when taking into account the temporal variation of field line. Also we calculated the resonance energy of electrons via cyclotron resonance by using Tsyganenko 2002 model and the upper frequency of the observed chorus emissions, where assumed an electron density of 5/cc at the plasmapause. The electron resonance energy became 8.5 keV to 2.4 keV, and the electron bounce periods became 2.6 sec to 4.9 sec. These results suggest that the electron bounce period through cyclotron resonance is not consistent with the observation results of repetition period of PA and chorus emissions. Meanwhile, geomagnetic pulsation having a high correlation with PA and chorus emissions was observed at Athabasca. It is expected that periodic modulation of a linear growth rate based on cyclotron instability plays an important role of the quasi-periodic scattering of energetic electrons.

In this presentation, we will discuss the repetition periods of southward-drifting PA and chorus emissions correlated with magnetic pulsations.

脈動オーロラを発生させる高エネルギー電子（数 keV～数十 keV）の間欠的な降り込みには、磁気圏の赤道付近における波動粒子相互作用によって VLF 帯ホイッスラーモード波が深く寄与していると考えられている。脈動オーロラの明滅周期を決める物理プロセスは未だ解明されていないが、従来の研究では、緯度に依存した電子のバウンス運動の周期との関係を示唆する結果と、発生緯度とは関係しない結果が報告されている。

本研究では、サブオーロラ帯であるカナダのアサバスカ（L 値：4.3、磁気緯度：61.2）で観測されたコーラス波動（100 kHz サンプリング）と、全天 EMCCD カメラ（110 Hz サンプリング）で観測した脈動オーロラの緯度変化に伴う周期性に着目した解析を行った。2015 年 2 月 17 日 10:00 UT から 30 分にわたって観測された脈動オーロラは赤道方向に伝搬するとともに、明滅周期が 15 秒から 8 秒へと短くなった。加えて、脈動オーロラと対応した周期をもつ、発生周波数が上昇するコーラス波動も観測された。コーラスの発生周波数はジャイロ周波数に比例することから、脈動オーロラの赤道方向の伝搬に対応した磁気赤道のコーラス波源が、より地球側に近づいたことを示唆するものである。

Tsyganenko 2002 モデルより得られるアサバスカをフットプリントとした磁力線の経路長の時間変化を考慮したとき、1 keV～100 keV の共鳴エネルギーをもつ電子のバウンス周期の変化は 1 秒以下となった。また、典型的なプラズマポーズの電子密度として 5 個/cc を仮定し、Tsyganenko 2002 モデルと観測されたコーラス波動の上端周波数を用いて、サイクロトロン共鳴する電子の共鳴エネルギーを算出した。このとき、電子の共鳴エネルギーは 8.5 keV から 2.4 keV となり、バウンス周期は 2.6 秒から 4.9 秒へと長くなる計算結果を得た。このことから、波動とサイクロトロン共鳴する電子のバウンス周期では脈動オーロラとコーラス波動の周期の観測結果を説明できない結果となった。一方で、今回の観測イベントでは、脈動オーロラの明滅とコーラス波動強度変化と高い相関関係をもつ地磁気脈動が観測されていた。よって、サイクロトロン不安定性に基づく線形成長率の周期的変調が電子の準周期的な散乱に影響を及ぼしていたことが考えられる。

本発表では、高時間分解能の全天 EMCCD カメラを用いた、緯度変化に対する脈動オーロラとコーラス波動の周期性変化に関して詳細に報告を行う。

夕方側オーロラオーバル内におけるオーロラアークの周期的生成

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Periodic generation of arcs within auroral oval on the duskside

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East-west aligned multiple arc structures often appear inside the auroral oval, regardless of the sign of IMF Bz. Some of them are known to show quasi-periodic motion. MHD waves including field line resonances have been suggested as one of the mechanisms explaining such a periodic motion. In the past study, Milan et al. (2001) reported that poleward moving auroral forms were observed in the postnoon sector, which showed a periodic bifurcation whose repetition period was 70 - 80 s. They implied that this periodicity was closely associated with field line resonances. In this paper, we examine the periodicity of the equatorward moving auroral arcs inside the auroral oval on the duskside. We show one of the events, observed by an all sky imager at Longyearbyen, Norway (78.2 N, 15.6 E, 75.3 MLAT) during a 3-h interval from 15:00 to 18:00 UT on November 28, 2013. Keograms created from the imager data clearly demonstrated characteristic periodic equatorward motions of the arc structure. The width and moving velocity of the arc structure were approximately 45 km and 220 m/s, respectively. A frequency analysis using Discrete Wavelet Transform showed that the optical forms moved equatorward repeatedly with periods of ~3 min, ~6 min and ~11 min. These periods are longer than that seen in the past studies. The magnitude of the electric field obtained by SuperDARN behind the arc structures was estimated to be 15 mV/m. In the presentation, we will discuss the possible generation mechanism of the periodic equatorward bifurcation of the arcs through comparison of observations with MHD simulation of Alfven waves traveling between the ionosphere and magnetosphere.

惑星間空間磁場 (IMF) の向きに関わらず, オーロラオーバル内には東西に延びるアーク構造が連なって現れ. その一部は, 主として極側に準周期的に移動することが知られている. このアーク構造の生成要因として, 磁力線共鳴に代表される磁気流体波に関連する物理過程が考えられている. Milan et al. (2001) による先行研究は, 昼間側で 70 - 80 秒の周期で極方向へ移動するアークを観測し, 磁力線共鳴によってこの周期性が再現されることを示している. 本研究では, ノルウェーのロングイヤービイエンに設置された高時間分解能全天イメージャによって, 2013 年 11 月 28 日 15 - 18 UT に, 夕方側オーロラオーバルの内部において観測された複数のアーク構造を解析する. このイベントでは, 輝度の大きな 1 本のオーロラが周期的に分裂を繰り返し, 赤道側へ移動していく様子が確認できた. オーロラオーバル内で極側へと移動するアーク構造については多く報告されているが, 赤道側へと移動していく構造については殆ど報告例がない. 光学観測データからアークの移動速度と水平方向の厚みを概算したところ, それぞれ約 220 m/s , 約 45 km であった. また, 分裂したオーロラアークの移動周期を確認するため離散ウェーブレット変換を用いた周波数解析を行った結果, 約 3 分, 約 6 分, 約 12 分の周期成分を持ってオーロラアークが赤道側へ伝搬していたことが明らかになった. 先行研究で確認されたアーク構造よりも本イベントのアーク構造の方が, 長い周期成分を持っていることが分かる. また, SuperDARN によって得られたプラズマ対流速度のデータからアーク構造の背景電場の大きさを見積もったところ約 15 mV/m であり, アークは背景のプラズマ対流速度にほぼ乗った形で移動していることが分かった. 発表では観測事実に基づいて得られたパラメータを初期条件として, 磁力線に沿って伝搬するアルフベン波のシミュレーションを行い, オーロラオーバル内のアーク構造が示す周期的赤道方向伝搬のメカニズムについて考察した結果を報告する.

全天イメージャと非干渉散乱レーダーを用いた2つのタイプの極冠オーロラの比較解析

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Comparison of two types of polar cap aurora: Simultaneous observations with ASI and ISR at Resolute Bay, Canada

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Polar cap auroras frequently appear in the polar cap region during the northward IMF conditions. In general, the polar cap is defined as a region of open magnetic field lines; thus, the polar cap aurora should be a phenomenon which originates from the magnetospheric lobe or solar wind. In this study, however, the term "polar cap aurora" is simply used as auroral features which appear at the polar cap latitudes. In the past studies, polar cap auroras have been roughly classified into the following two types. One is a single isolated arc showing relatively small time variation. This type of arc has a structure extending towards the sun and then is sometimes called as sun-aligned arc (SAA). The other type of polar cap aurora is composed of multiple arcs propagating poleward intermittently and is sometimes called as poleward-moving auroral arcs (PMAA). This type of polar cap aurora is mostly observed in the morning side. The source regions and generation mechanisms of these two types of polar cap aurora have not been revealed so far. In particular, for the latter type, its generation mechanism has not been understood at all mainly due to limitations in the time resolution of the radio and optical observations. To answer these questions, we have carried out simultaneous observations of polar cap aurora by using an all-sky airglow imager (Optical Mesosphere Theremosphere Imagers: OMTIs) and an incoherent scatter radar (Resolute Bay Incoherent Scatter Radar: RISR) at Resolute bay, Canada. Then, we investigated temporal-spatial evolution of the parameters of plasma in the vicinity of the arcs. Especially, we clarified the differences between an isolated single arc on the nightside (SAA-type) and multiple arcs propagating poleward in the morning side (PMAA-type).

During two intervals respectively on November 14, 2009 and January 6, 2013, the SAA-type and PMAA-type polar cap auroras were observed at Resolute Bay. The one observed on November 14, 2009 is categorized as the SAA-type. According to the radar observation, the SAA showed a velocity shear structure of 900 m/s. In this case, since the direction of line-of-sight (LOS) and the shear structure are almost parallel, we have assumed that the background convection speed and projection of LOS ion velocity to the horizontal plane are identical. We also examined the altitude distribution of the electron density variation associated with SAA. By subtracting an 1-hour average profile, we estimated the altitude of the peak electron density to be around 230 km. The event observed on January 6, 2013 is categorized as PMAA-type in the morning side. According to the optical observation, PMAA was moving poleward at a speed of 200-300 m/s. During this interval, the radar observations showed an existence of velocity shear structure of 500 m/s superimposed on the background convection of ~200 m/s. This result indicates that PMAA was moving with the background convection velocity. In addition, the magnitude of the shear structure should have been underestimated because the radar beam direction and the motion of PMAA were almost perpendicular. Therefore, the shear structure of PMAA could be comparable to the shear structure seen in the case of SAA (900 m/s). We also investigated the altitude profile of the electron density during PMAA and found that the peak altitude of PMAA was around 210 km. This result indicates that the energy of precipitating electrons was several hundred eV. In summary, we found that the two types of polar cap aurora (PMAA and SAA) have similar electrodynamic structures and precipitation characteristics. This implies that the source of SAA and PMAA is common in the magnetosphere.

極冠オーロラは，IMF が北向きのときに，磁気緯度 75 度以上の極冠域で頻繁に観測される現象である．極冠域は開いた磁力線の領域として定義されるため，本来，極冠オーロラは太陽風もしくは磁気圏ローブ領域にその起源を持つものを指すが，本研究では極冠の緯度に現れるオーロラを広く示すものとして用いる．極冠オーロラは，過去の研究から，大きく 2 つのタイプに分類されることが知られている． 1 つは，孤立した状態で現れる比較的時間変化の少ないアークで，太陽方向に伸びた構造をしており，Sun-aligned arc（SAA）とも呼ばれるものである．もう 1 つは Poleward-moving auroral arcs（PMAA）と呼ばれ，複数のアークが極方向に間欠的に伝搬する時間変化の激しい極冠オーロラである．この種の極冠オーロラは，朝側の地方時で観測されることが多いが，時間分解能の限界のために，解明されていない部分が多い．これら 2 つのタイプの極冠オーロラは，発生の物理メカニズムやソース領域が異なることが予想されるが，特に後者のタイプについては，未だにその起源が明らかになっていない．これは，2 つのタイプの極冠オーロラについて，その近傍の電磁気学的構造を直接的に比較し，相違点を明らかにすることが行われて来なかったことに起因する．本研究では，カナダレゾリュートベイに設置されている全天大気光イメージャ（Optical Mesosphere Theremosphere Imagers: OMTIs）と非干渉散乱レーダー（Resolute Bay Incoherent Scatter Radar: RISR）を組み合わせて，極冠オーロラの同時観測を行い，アーク周辺におけるプラズマのパラメータの時空間発展について調べた．特に，孤立型のアークが存在する場合（SAA）と，朝側で複数のアークが極方向に伝搬する場合（PMAA）についてその電磁気学的構造を直接的に比較し，それぞれの極冠オーロラの性質と起源を明らかにすることを目的とする．この目的のために，2009 年 11 月 14 日と

2013 年 1 月 6 日に得られた 2 つの同時観測事例の解析を行った．

2009 年 11 月 14 日に得られた同時観測事例においては SAA 型の極冠オーロラが観測された．レーダー観測から，SAA の近傍には 900 m/s 程度の対流速度のシア構造が存在していることが分かった．この見積もりでは，レーダーの視線方向とシア構造がほとんど平行であったことから，視線方向イオン速度の水平面への射影が背景の対流に一致すると仮定している．次に，SAA の電子密度高度分布を調べた．極冠オーロラの発生時間の前後一時間の平均プロファイルからの差分を導出し，オーロラによる電子密度のピーク高度を求めた．その結果，SAA のピーク高度は 230 km であることがわかった．2013 年 1 月 6 日に得られた同時観測事例においては PMAA 型の極冠オーロラが観測された．光学観測から PMAA は極方向に 200-300 m/s で運動していることが分かった．このとき，レーダー観測から，200 m/s 程度の背景対流に乗って，500 m/s 程度のシア構造がアークの近傍に存在していることが分かった．この結果は PMAA の運動と背景対流速度がほぼ一致していることを示している．また，レーダーの視線方向と PMAA の運動方向がほとんど直交することから，シア構造のイオン速度は真の値より過小評価されていると考えると，PMAA のシア構造は，SAA のシア構造（900 m/s）と同程度の速度を持つことも分かった．PMAA に伴う電子密度変動の高度分布を調べたところ，電子密度増大のピーク高度は 210 km 程度であることがわかった．この結果は，降下粒子のエネルギーが数百 eV であることを示している．また，PMAA と SAA のピーク高度の比較から，どちらも似通ったソース領域を持つことが推測される．以上の結果から，PMAA と SAA は似通った電磁気学的構造とソース領域を持つと考えられる．今後は高空間分解能のデータを用いることで，空間構造をより正確に導出していくとともに，エネルギー分布と広域構造にも着目した考察を行っていく予定である．

昼間側脈動オーロラの統計的研究

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Statistical study of dayside pulsating aurora

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http://www.sgepss.org/

Pulsating aurora normally occurs after a substorm breakup in the midnight sector, often observed to persist through the morning sector and beyond. Indeed, it has also been observed on the dayside; however, the characteristics of the dayside pulsating aurora are poorly known. A handful of observational studies have been reported, but the results are somewhat disputable because most of the studies had non-uniform sampling of the dark dayside region. Furthermore, the previous studies used photometer data, with which the spatial characteristics of the pulsating aurora cannot be examined. To determine both temporal and spatial characteristics of the pulsating aurora, we have studied three years of all-sky image data obtained at the South Pole station. Because of its unique geographical location, the station has 24 hours of darkness during the austral winter from April to August, providing an ideal platform for studying dayside aurora. In a preliminary survey of the data, we have identified the pulsating auroras in 198 days out of 365 days of observations. The magnetic local time (MLT) distribution of the occurrence peaks between 9:00 and 11:00, but shows no or little dependence on the geomagnetic activity. In many events, pulsating patches initially appear as east-west aligned arc segments and later in the afternoon sector develop into large, diffuse patches, which occasionally fill a large part of the field of view. Using the long-term data, we will statistically examine both temporal (occurrence rate, duration and pulsation period) and spatial (sizes and shapes) characteristics of the dayside pulsating aurora.

Postnoon auroral spotsの特性

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Characteristics of the postnoon auroral spots

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We examined auroral image data from an all-sky imager in order to understand when and how the postnoon auroral spots are created. From the detailed examination of the data obtained during two winter seasons (2013-2014, and 2014-2015), we have found that the postnoon auroral spots consist of poleward-drifting multiple arcs. Each poleward-drifting arc distorts into a folding structure at the final stage of the poleward drift, and becomes even brighter. We report the temporal characteristics of the postnoon auroral intensification, and discuss what controls the beginning of the poleward drift of the postnoon auroral intensification, which is thought to be an initial feature of the postnoon auroral spots.

真昼過ぎのMLTにおいてオーロラが局所的に明るくなる現象，いわゆるpostnoon auroral spotsの成因は未だ明らかではない．これまでの研究の中には，磁気圏の低緯度境界層とプラズマシートの境界で生じる速度シアによるKelvin-Helmholtz instabilityを原因と考えるものもある．しかし，このような流れのシア構造は, 磁気圏内において常に生じていると考えられ, 定常的ではないpostnoon auroral spots現象の原因になり得るのかどうかははっきりしない．本研究では，地上全天イメージャーによって冬季の2シーズン (2013-2014および2014-2015) に得られたオーロラデータをもとに，postnoon auroral spotsがどのような時にどのような形で現れるのかを調べた．1400-1600 MLTで観測されたオーロラを詳細に解析した．取りあげた事例のうち，発光強度の増大が顕著なイベントでは，オーロラのアーク構造が極方向にドリフトし，輝度が最大となったところでfoldしていることがわかった. この極向きドリフトに対して，Tsyganenkoモデルを用いて磁力線の磁気圏マッピングを行うと，磁気圏の低緯度境界層からプラズマシート付近における下流方向かつマグネトポーズ方向の動きになるものの，その速度は，磁気圏のプラズマ速度を考えると非現実的であることもわかった. また，取りあげた事例の中には，明確な発光強度上昇がほとんど起こらないケースも多くあった．postnoon auroraの発光強度の上昇に対する時間変化特性を明らかにし，postnoon auroral spotsへと発展すると考えられるオーロラの極方向へのドリフトの開始を何がコントロールしているのかを議論する．

Simultaneous Akebono satellite and ground-based observations of MF/HF auroral radio emissions

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MF/HF auroral radio emissions are generated in ionospheric *F* region altitudes and propagate to the ground and outward to space. At ground level, three types have been identified above 1 MHz: auroral hiss, medium frequency burst (MFB), and auroral roar. Auroral roar-like signals detected in space in a frequency range have been reported by several papers, which were termed terrestrial hectometric radiation (THR) by *Oya et al.* [1985]. We survey long-term observation data obtained by ground-based passive receivers installed in Iceland and Svalbard and the Plasma Waves and Sounder experiment (PWS) mounted on the Akebono satellite to find simultaneous measurements of MF/HF auroral radio emissions above 1 MHz. This data set includes two simultaneous appearance events, during which frequencies of aurora roar and MF burst detected at ground are different from that of Terrestrial Hectometric Radiation (THR) observed by the Akebono satellite passing over the ground-based stations. This frequency difference supports the previously proposed idea that auroral roar and THR are generated at different altitudes across *F* peak. There is no possibility that simultaneous observations indicate the identical generation region of auroral roar and THR. When the Akebono satellite passing over the ground-based stations detects THR, auroral roar and/or MF burst does not always appear (at 90 percent in this study). This tendency is explained in terms of the idea that the Akebono satellite can detect THR emissions coming from a wider region, and a considerable portion of auroral roar emissions generated in the bottomside *F* region is absorbed in the *D/E* regions.

東向きに拡大するオーロラサージのオーロラトモグラフィ解析結果

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Results of auroral computed tomography analysis of eastward expanding auroral surges

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We present results of auroral computed tomography (ACT) analysis of three eastward expanding auroral surges (EEASs) observed on March 9, 2013. We conducted a campaign of auroral observations in northern Scandinavia using multiple imagers and the European Incoherent Scatter (EISCAT) radar from March 5 to March 9, 2013. Three EEASs were observed intermittently at about 15-minute intervals in the post-midnight sector (01:55-02:40 MLT) by monochromatic (428nm) all-sky EMCCD imagers at Tromso (69.6N, 19.2E), Norway, Kilpisjarvi (69.0N, 20.9E), Finland, and Abisko (68.4N, 18.8E), Sweden, with an exposure time of about 2 seconds and an sampling interval of about 10 seconds. We applied the ACT technique to these EMCCD image data. The ACT allowed us to accurately estimate horizontal sizes and drift velocities of the surges. In addition, it was found that the altitude of maximum emission was temporally stable and confined to a narrow range between 96 km and 114 km. The averaged energy of precipitating electrons that was estimated by the ACT with a traditional model for electron auroral emission (Rees 1993) was mainly distributed between 2 keV and 7 keV with a maximum at 4 keV. Furthermore, we found that the averaged energy increases with increasing total energy flux of precipitating electrons. The relation between the averaged energy and total energy flux may be consistent with a theory in which electrons are accelerated by a field-aligned potential difference (Ono et al., 1993). On the other hand, the relation between the averaged energy and the width of discrete arc was not clear, because the averaged energy showed a strong dependence on the location of discrete arc, which may be explained by artifacts that appear at the edge of images. In the presentation we also show a substorm observed by a campaign of auroral tomography observations in March, 2015.

s-CMOSカメラによる脈動オーロラの内部変調構造の観測

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Internal modulations of the pulsating aurora observed by s-CMOS camera

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A pulsating aurora (PsA) is a kind of the diffuse aurora, and tends to appear in the recovery phase of a substorm between midnight and dawn sector. PsA shows irregularly switching on and off in the brightness with typical durations in the range 2-20 s. Quasi-periodic fluctuation at a frequency of 3 +/- 1 Hz is sometimes superimposed on the pulsation. Recently, several studies reported the existence of internal modulations with higher than 10 Hz, but characteristics as well as the origin of the fast modulations have not been understood.

We have installed a s-CMOS camera at the Poker Flat Research Range in Alaska, US, to observe the high-frequency modulations in the PsA. As an example of the data analysis, we show the data on November 2014. During the observation, the number of pixels of the s-CMOS camera is 512∗128. The sampling frequency of the s-CMOS camera was 200 Hz. Different types of luminosity modulations are found: (A) internal modulations embedded in main modulations, (B) main modulation without internal modulation, and (C) internal modulation without significant main modulations. These pattern are often seen as successive variations, suggesting time variations of the generation process of chorus waves at the magnetosphere. The frequencies of the internal modulations for Type (A) are widely distributed from a few Hz to ˜10 Hz. The average frequency and standard deviation of the internal modulations within a main modulation have a good correlation, indicating each main modulation has different kinds of the internal modulations.

脈動オーロラは、明滅を伴うディフューズオーロラの一形態であり、主にサブストームの回復相において真夜中から明け方において観測される。脈動オーロラの明滅には、主脈動と内部変調と呼ばれる異なる時間スケールの変動が存在し、それぞれ数秒から数十秒および数十ミリ秒から数百ミリ秒の周期を有している。内部変調の時間スケールは、従来約 3Hz とされてきた。しかし、近年の研究では、10Hz よりも速い高速の内部変調の存在も報告されている。

本研究グループでは、脈動オーロラの時間変動の特徴、特に内部変調の特性を詳細に調べるために、高速撮像が可能な s-CMOS カメラを、アラスカの Poker Flat Research Range に設置し観測を行い、内部変調構造に関する統計的な解析を進めている。一例として、2014 年 11 月 21 日のデータの解析を行った。このとき、s-CMOS カメラは、サンプリング周波数 200 Hz、および 512∗128 pixel で観測を行っていた。解析の結果、脈動オーロラの内部変調の輝度変化は、(A) 数秒周期の主脈動および主脈動に重畳する内部変調が観測されるもの、(B) 主脈動のみで内部変調を伴わないもの、(C) 主脈動的な輝度変化がなく内部変調のみしか観測されないものと、複数の形態が確認された。また、空間のある点における輝度の時間変化に注目した場合、上記の (A)-(C) のタイプが時間的に次々と変化していく様子も観測された。一方、タイプ (A) として観測される主脈動を対象に、その内部変調周波数の統計解析を行ったところ、内部変調周波数は数 Hz から 10Hz 以上に広く分布していることがわかった。また、一つの主脈動における平均内部変調周波数とその分散とはよい相関があることがわかり、主脈動が内包する内部変調構造は均一な特性ではないことが示唆される。

伝搬渦電流の内部に見られる高速フリッカリングオーロラ

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Fast flickering aurora within traveling current vortices

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Flickering auroras have typical frequencies of 5-15 Hz which correspond to oxygen ion cyclotron frequency. The formation mechanism has been therefore assumed as Landau resonance between electrons and electromagnetic ion cyclotron waves in the auroral acceleration region. However, many fast flickering auroras have recently been found at much higher frequency of up to 50 Hz, which may be contradictory to the standard theory. The purpose of this study is to investigate the formation mechanism of the fast flickering aurora. Two identical imaging systems were installed at Poker Flat Research Range (PFRR) in Alaska since February 2014 and conducted observations during two winter seasons. 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. The sampling rate of the one system is 50 frames per second (fps), while another system uses a sub-array option to enhance the sampling rate up to 200 fps. We used RG665 sharp cut filter only for the sub-array imaging. During a magnetic storm event on February 19, 2014, we found interesting variations in ground-based magnetometer observations nearby PFRR associated with the appearance of fast flickering auroras. It is found that the fast flickering auroras repeatedly appear when the magnetic field show impulsive variations (5-10 min, 100-200 nT amplitude). From the phase difference of the impulsive variations of Bx, By, and Bz components, traveling Hall current vortices with the upward field-aligned current can be identified. We discuss the formation mechanism of the fast flickering aurora associated with the traveling current vortices.

2015年6月22日SCイベントに伴うオーロラ活動

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Auroral activity observed during the SC event on June 22 in 2015

Akira Kadokura[1]
[1] NIPR

Auroral activity observed at Syowa Station during the SC event on June 22, 2015 will be analyzed.
Some features of this event are as follows:
(UT)
18:03 Shock arrival at ACE position
18:33 SSC at Kakioka, maximum:+104nT
18:33:30 SC magnetic variation start at Syowa
18:34 Auroral variation appear at lowest horizon
18:40 Poleward expansion of auroral arc
18:40:30 Break of arc -> diffuse spread
19:32 poleward expansion again
19:54 spread from higher latitude to lower latitude
20:30 going back to calm

During this period, following optical instruments were operated at Syowa Station:
- All-sky Monochromatic imagers(427.8,557.7,485.0,480.5nm)
- All-sky panchromatic TV camera
- Multi-color Scanning Photometer

During this period, very bright proton auroral emission over 500 R was observed.

In our presentation, details of temporal variation of auroral activity will be shown.

2015年6月22日のSCイベントに伴って、南極昭和基地で観測されたオーロラ活動について報告する。このイベントの特徴を下記に列挙する：
(UT)
18:03 Shock arrival at ACE position
18:33 SSC at 柿岡、最大+104nT
18:33:30 SC 地磁気変化開始 at 昭和基地
18:34 オーロラ活動に変化開始
18:40 ここまで、オーロラアークの高緯度側への拡大
18:40:30 アークの崩壊 -> 全天 diffuse
19:32 再び poleward expasion
19:54 高緯度側から低緯度側への拡大
20:30 静穏化

この期間、昭和基地では、下記の観測器によりオーロラ光学観測が行われていた：
・全天単色イメージャ（427.8,557.7,485.0,480.5nm)
・全天白黒TVカメラ
・8色掃天フォトメータ

このイベントの特徴の1つとして、上記の時間帯に、最大輝度500Rを超える非常に明るいプロトンオーロラの発光が見られたことが挙げられる。

本講演では、こうしたオーロラ活動の時間変化の詳細の紹介を行う。

SWARM衛星で観測された磁場変動データによる磁気圏内乱流プラズマの分布

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Distribution of turbulent plasma in the magnetosphere estimated by the SWARM magnetic data.

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LEO satellites observe the magnetic fluctuations with period from a few second to a few tens of seconds along their orbits in high-latitudes.
It has been proposed that these are mainly caused by the spatial structures of the field-aligned currents(FACs).
However, since LEO satellites before the SWARM were single, the studies still have theoretical assumptions.
In this study, at first, we will show that these fluctuations are the manifestations of the spatial structures of the FACs by using the data obtained by SWARM-satellites during initial two months.

Second, based on the above, we assume that these fluctuations mainly consist of the spatial variations, and apply spectral analysis to see the characteristics of the spatial structure of the FACs.
From the above analyses, we confirm that the fluctuations with period from about 2 second to about 30 second can be regarded as the manifestations of the spatial structure of FACs.
We also discuss about temporal variations of these structures.

Then we project the area of fluctuations on the equatorial plane of magnetosphere, i.e., the plasma sheet, by using the Tsyganenko model, and estimate the characteristics of turbulence.

高緯度電離層において低高度衛星はその軌道に沿って数秒から数十秒の周期を持った磁場の変動を観測する。
これらのほとんどは過去の研究により、沿磁力線電流の空間構造によるものであるとされてきた。
しかし、SWARM 衛星以前の低高度衛星はどれも単機であり、それらの研究はあくまで理論的仮定にとどまっている。
本研究では、SWARM 衛星によって得られた初期 2ヶ月のデータを用いて、まずこれらの磁場変動が沿磁力線電流の空間構造の現れであることを示す。
次にそのことをふまえ、これらの磁場変動が主に沿磁力線電流の空間構造によって構成されていると仮定し、周波数解析により空間構造の特性を見る。
以上の解析により、我々は極域で観測される短周期の磁場変動は周期約 2 秒から数十秒のものについては沿磁力線電流の空間構造の現れと見なすことができることを明らかにした。

また、これらの空間構造についてその時間変化についても議論する。

更にこれらの磁場変動をチガネンコモデルを用い、プラズマシート等磁気圏赤道面に投影し、乱流領域の特性及び分布を推定する。

A review of magnetopause and boundary layer studies in 2013-2015

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The presentation will review advances made for the last two years in our understanding of planetary magnetopauses, their boundary layers, their roles, and the processes occurring there. The topics to be covered include, but are not limited to, current sheet structures, magnetic reconnection, Kelvin-Helmholtz instability, ULF and high-frequency wave excitation, plasma heating, cold ion effects on magnetopause reconnection, polar cusps, plasma depletion layers, heliopause crossing by Voyager-1, and the prospects for the Magnetospheric Multi-Scale (MMS) mission that was successfully launched on 12 March 2015. This is an extended and more informative version of my presentation that was given in the IAGA Division III reporter review session at the IUGG 2015 meeting.

Propagation of electric fields during Pi2 pulsations based on multi-point observations

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Pi2 pulsations are irregular oscillations in the period range from 40 s to 150 s, and their source lies in the nightside magnetosphere. Electromagnetic disturbances associated with Pi2 pulsations propagate through the magnetosphere by magnetohydrodynamic waves. The compressional fast mode waves are launched by localized plasma sheet fast flows and propagate into the inner magnetosphere [e.g., *Lee*, 1996; *Lee and Kim*, 1999]. On the other hand, the velocity shears at the edge of these flows excite shear Alfven waves, which transport magnetic shear and carry field-aligned currents along magnetic field lines [e.g., *Keiling et al.*, 2006, 2008]. These propagation processes have been proposed based on several previous studies using magnetic field observations and numerical simulations. However, there have been few results by electric field observations although the electric field is an important quantity for detecting Pi2 pulsations than magnetic field. In addition, Pi2 pulsations are known to be associated with substorms. *Nishimura et al.* [2012] shows evolution of auroral streamers at the substorm onset time followed by Pi2 pulsations after a few minutes, using ground-based observations. It suggests that Pi2 pulsations are driven by multiple plasma sheet flow bursts to earthward. However, the propagation mechanism of Pi2 pulsations and associated phenomena such as auroral streamers are not only governed by plasma sheet flow bursts. In the mid-low latitude, Pi2 pulsations are known to be driven by cavity mode resonance that a fast mode impulse associated with substorm onset propagates into the plasmasphere and trapped between the plasmapause and ionosphere. Since there are several propagation processes of electromagnetic energy that can explain the relationship between the substorm onset, auroral streamers, and Pi2 pulsations, further validations by multi-point observations in the magnetosphere-ionosphere coupled system are required.

Motivated by these issues, we investigate the evolution and propagation of the electric field during Pi2 pulsations using multiple observations. We use the magnetospheric electric and magnetic fields obtained by THEMIS (5 probes), Van Allen Probes (VAPs; 2 probes). Magnetospheric magnetic field data from GOES 13 and 15 are also used. The ionospheric electric field data are obtained from SuperDARN (high latitude) and HF Doppler (mid latitude) radars. Pi2 events are identified by the low-latitude geomagnetic field detected at Kakioka and AL index.

We will investigate several events when satellites and radars cover the entire region of the inner magnetosphere, and evaluate the possible propagation process of the electromagnetic energy associated with Pi2 pulsations.

GEMSIS-RC、RBに基づく電子とPc5単色波のドリフト共鳴のピッチ角依存性

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Pitch angle dependence of drift resonance of relativistic electrons with a monochromatic Pc5 wave based on GEMSIS-RC and RB models

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Radial transport of relativistic electrons due to Ultra Low Frequency (ULF) waves in the Pc5 frequency range (1.67mHz - 6.67mHz) is one of important candidates to accelerate the outer radiation belt electrons. The acceleration is considered as a result of the drift resonant process. This process is a resonant mechanism between the electron drift motion in the dipole-dominated magnetic field configuration and the electromagnetic fluctuations of Pc5 waves in the inner magnetosphere. The resonance violates the third adiabatic invariant of electrons, while it conserves the first and second adiabatic invariants. Recent studies have pointed out that the radial transport due to the drift resonance can produce one or more localized peaks in radial profile of the phase space density (PSD) [Degeling et al., 2008]. Ukhorskiy et al. [2008] indicated that collective motion of outer belt electrons can exhibit large deviations from radial diffusion. Since the peak in PSD is considered as an evidence of local acceleration [e.g., Reeves et al., 2013], these studies have raised fundamental questions in the radiation belt electron acceleration. Thus, it is important to understand fundamental characteristics of the collective motion of the electrons against the Pc5 waves in the inner magnetosphere.

In this study, we combined 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 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 conducted Pc5 wave simulation with GEMSIS-RC, and then the obtained time variations of the magnetic and electric fields are used as inputs to GEMSIS-RB to calculate the electron transport due to the Pc5 wave. To investigate fundamental behavior of the transport, we investigated effects of a monochromatic wave on the radial transport. The result shows combination of these models can reproduced the localized peaks in PSD due to phase bunched transportation and electrons with oblique pitch angle (~70 degrees) are transported deeper inside to small L region than 90 degrees electrons. In this presentation, we will discuss possible mechanisms to cause the pitch angle dependence of the electron radial transport .

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放射線帯MeV電子増加時の静止軌道磁場変動特性

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Magnetic Variations at the Geosynchronous Orbit during MeV Electron flux Enhancement in the Radiation Belt

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In this study, we analyze the magnetic variations observed by GOES 10 and 11 satellites during the MeV electron flux enhancement event on 26-30 October, 2008. Former analysis of the ground magnetic variations observed at H057 (Maglat.=-66.42, L=6.25) and Skallen (Maglat.=-66.42, L=6.25) in Antarctica, suggests that the troidal oscillation in the magnetosphere with the range of Pc5 wave is predominant with low m number (˜2). On the other hand, the obvious MLT dependence of the Pc5 power is observed by two GOES satellites, that is, the Pc5 power is predominant in the daytime sector compared to that in the morning sector during the MeV electron enhancement event. This signature is pronounced in X and Y components (GSM coordinate system) of Pc5 power at the GOES satellites, though the Z component of the Pc5 does not show the obvious difference in MLTs.

The present result suggests that both the troidal oscillation and compressional wave occur at the GEO during the high speed solar wind event, and the Filed Line resonance (FLR) of the ULF wave causes the non-uniform Pc5 powers in different MLTs. This also indicates the compressional wave of Pc5 may play an important role in the modulation of the troidal Pc5 oscillations.

放射線帯における相対論的エネルギー電子 (MeV 電子) 増加の加速機構の 1 つとして ULF 波動によるドリフト共鳴モデルが提唱されているが、ドリフト共鳴が効率的に発生するためには、磁気圏中において経度方向波数の小さいトロイダル振動が寄与すると考えられる。これまでの解析において、南極無人磁力計ネットワークのうち、H057 (磁気緯度: -66.42, L=6.25) と Skallen (-66.42) の 2 点における Pc5 帯（周期 150-600 秒）の ULF 波動の解析により、磁気嵐主相から回復相の期間において Pc5 波動の強度は強くなるが、静止軌道で MeV 電子が増える磁気嵐の回復相には、南北成分の卓越および経度方向波数の減少安定が特に顕著であることが明らかになった。これは、磁気嵐の回復相において、磁気圏ではグローバルなトロイダル振動が卓越していることを示唆しており、ドリフト共鳴加速を支持する観測結果であった。

本研究では、静止軌道の GOES10（西経 60 度）及び GOES11（西経 135 度）の磁場 3 成分データ（0.512 秒サンプリング）を用い、MeV 電子増加時の磁気圏中の ULF 波動の解析を行った。2008 年 10 月 28 日に到達した高速太陽風により 10 月 29 日に Pc5 波動の強度はすべての MLT で増大が見られた。Dst 指数は、29 日 0700UT に-22nT の弱い減少を示し、その後 31 日にかけて-10nT 程度を継続していた。AE 指数は、30 日 1400UT 頃より増加し最大で 900nT (0700UT) に達した。GOES の>2MeV 電子フラックスは 30 日 12-21UT の間に増加し 104PFU に達した。一方で、MeV 電子増加時の GOES 衛星における ULF 波動のパワーには明瞭な MLT 依存性が見られた。MeV 電子の増加に伴って GOES11(午前側）に比べ GOES10（昼側）では強い Pc5 波動が全成分で相対的に卓越した。Z 成分 (GSM 座標系）については、GOES11 においても Pc5 帯では増大が見られた。

これらの結果は、圧縮波としての Pc5 が MeV 電子の加速に寄与している可能性を示唆しており、放射線帯 MeV 電子加速時における磁気圏中での Pc5 波動の伝播機構の重要性を示している。

Simultaneous observation of field-aligned current with QZS and MAGDAS observatories - using FA coordinate

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FAC (Field-Aligned Current) is a current connecting the magnetosphere and the ionosphere. It is important to research FACs to understand the structure and dynamics of the magnetosphere and substorms. There are many reports about FAC observations. They used data from, e.g., geostationary orbit satellites, polar-orbit satellites and ground magnetometers. However, there are only small number of reports about a FAC simultaneously observed for a long time by a satellite and a ground observatory is. Thus, we analyze magnetic data from QZS (Quasi-Zenith Satellite) operated by JAXA and MAGDAS (MAGnetic Data Acquisition System) operated by International Center for Space Weather Science and Education (ICSWSE), Kyushu University. QZS has a tilted geostationary orbit and stays near the meridian plane of Japan. Thus, the footpoint of the magnetic field line running through QZS exists near Siberian MAGDAS stations, and we can observe a phenomenon along a magnetic field line for a long time. Furthermore, since QZS stays at high latitudes in space, we can expect to clearly identify FACs. In this study, we use the QZS magnetic field data expressed in FA (Field-Aligned) coordinates and the magnetic field data from Siberian MAGDAS stations, identify simultaneously-observed FAC events, and study them on a statistical basis. An example event took place on April 9th, 2011. Disturbances of the magnetic field were observed at 17:20~17:35UT. The observation can be interpreted as follows: A current circuit which was caused by a substorm moved westward in the morning-side region.

FAC（Field-Aligned Current; 沿磁力線電流）は磁気圏と電離圏を繋ぐ電流で、磁気圏の構造やサブストームなどの現象において非常に重要である。FAC についてはこれまでに静止軌道衛星や極軌道衛星、地上観測など様々な観測が行われてきた。しかし、同一の FAC を衛星と地上観測で長時間同時に観測した報告例は少ない。そこで本研究では、JAXA の運用する衛星 QZS（Quasi-Zenith Satellite; 準天頂衛星）と九州大学国際宇宙天気科学・教育センターが中心となり運用する地磁気観測ネットワーク MAGDAS（MAGnetic Data Acquisition System ）の同時観測磁場データを用いて解析を行う。QZS は静止軌道に傾斜角を持っており、日本の子午面近くに滞在する。そのため、これを通過する磁力線の footpoint が MAGDAS シベリア観測点の付近にあり続けるので同一の磁力線上を伝わる現象を長時間同時観測できる。また、QZS は磁気圏内高緯度領域に長時間滞在するため、FAC を明瞭に観測することができると考えられる。本研究では、FA（Field-Aligned）座標系で表現した QZS 磁場と、シベリア MAGDAS 磁場から、FAC 同時観測例を同定し統計的に解析する。一例として、2011/04/09 の 17:20~17:35UT にイベントが観測された。このイベントは朝側領域において、サブストームに伴って形成された電流回路が西向きに流されたものと解釈できる。

Solar zenith angle dependence of composition, velocity and temperature of ion outflows

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Recent satellite observations and simulations have clarified that (especially O^+) ion outflows from the ionosphere play an important role in abrupt changes in the ion composition in the plasma sheet and ring current during geomagnetic storms. The energy of outflowing ions is an important factor to understand the transport path of the ions to the magnetosphere. To clarify how strongly ionospheric conditions (sunlit or dark) affect ion outflows, we investigated solar zenith angle (SZA) dependence of composition, velocity and temperature of outflowing ions above 10 eV using the data obtained by the FAST satellite at 3000-4150 km altitude from 7 January 1998 to 5 February 1999.

We discriminated ion beam events from non-beam (related to transverse heating) events, and studied separately. At this altitude range, almost all of beam events were observed under ionospheric dark conditions. For the beam events, the O^+/H^+ flux ratio does not depend on SZA (average: ˜0.25), while the flux ratio decreases with increasing SZA for the non-beam events. Since the flux ratio of ion beams reflects the ion composition at the lower end of the auroral acceleration region, the averaged flux ratio indicate the typical ion composition at the lower end of the auroral acceleration region. The ion composition below ˜3000 km is probably not suitable to develop the auroral acceleration region under sunlit conditions.

For the non-beam events, the parallel streaming energy and temperatures (perpendicular and parallel) of ions tend to increase with increasing SZA. This result indicates that the solar illumination affects energization of outflowing ions at least below 3000 km altitude. Under dark conditions, the parallel streaming energy and the parallel temperature of ions in the non-beam events often exceeded ˜10 eV, while those rarely exceeded 10 eV (˜1 eV in most of cases) under sunlit conditions. The perpendicular ion temperature in the non-beam events was mostly ˜10-30 and ˜15-200 eV under sunlit and dark conditions, respectively. Our previous study showed that ion outflows (especially O^+) with large fluxes, which would have a large impact for the magnetospheric physics, occur mostly under sunlit conditions. Thus, the solar illumination enables the ionosphere to cause ion outflows with large fluxes, while it would suppress energization of ions at least below ˜3000 km altitude.

Additionally, we found that the outflowing ion number flux positively correlates with the parallel streaming energy of ions under sunlit conditions, while no clear correlation between the outflowing ion number flux and perpendicular or parallel ion temperatures. Thus, it is expected that there is a physical connection between the parallel streaming energy and the ion number flux under sunlit conditions, and it is important to clarify how the ions gain the parallel streaming energy (˜several eVs) below ˜3000 km altitude for understanding of the driving mechanism of ion outflows with large fluxes. Weak parallel electric fields and/or perpendicular heating at low altitudes in the cusp/cleft and the auroral zone would be the candidate. Since the parallel streaming energy is very small (below ˜10 eV), detailed ion measurements that include the energy range below ˜10 eV are essential in future for further investigation at least below ˜3000 km altitude.

リングカレント領域へのイオン供給過程におけるプロトンと酸素イオンの違いについて

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Deeper and earlier penetrations of oxygen ions than protons into the inner magnetosphere observed by Van Allen probes.

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It is observationally known that proton and oxygen ions are main components of the ring current during magnetic storms and that the proton and oxygen ions are considered to have different source and supply mechanisms. However, detailed properties of the ion supply and their dependence on ion species is far from well understood. To characterize the ion supply to the ring current during magnetic storms, we report studies of the properties of energetic proton and oxygen ion phase space densities (PSDs) during the April 23-25, 2013, geomagnetic storm observed by the Van Allen Probes mission. We used energetic ion (˜50 - ˜600keV protons, ˜140 - ˜1100keV oxygen) and magnetic field data obtained by the RBSPICE and EMFISIS, respectively, on the Van Allen Probes.

We calculated ion PSDs for the specific first adiabatic invariant, mu (0.3 < mu < 12 keV/nT), and ion pitch angles near 90 degrees as a function of L for each spacecraft orbit. The results show that both proton and oxygen ions penetrated directly to L<5 during the main phase of the magnetic storm. Protons with smaller mu values (mu = 0.3 and 0.5 keV/nT) penetrated earlier than those with larger mu values (mu = 1.0 keV/nT). This result appears consistent with the energy dependence of the Alfven layer. The timing of oxygen ion penetration is approximately the same for all mu values (mu = 0.8, 1.0 and 1.2 keV/nT). The observations also show that oxygen ions penetrated more deeply in L and earlier in time than protons for the same mu value (mu = 1.0keV/nT). These results suggest that the source of the transported oxygen ions is located closer to the Earth than the inner edge of protons. The results imply the importance of the contribution from subauroral oxygen ions to the storm-time ring current. We will also discuss the possibility of non-adiabatic acceleration of oxygen ions in the inner magnetosphere.

磁気圏－電離圏結合系におけるフィードバック不安定性への磁場曲率効果

渡邉 智彦 [1]
[1] 名大

Magnetic curvature effects on the feedback instability in M-I coupling system

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The feedback instability in the magnetosphere-ionosphere coupling system has been discussed as a theoretical model which is a possible mechanism to explain spontaneous growth of quiet auroras. It can successfully explain formation of local current circuit and enhancement of ionospheric density associated with auroral arc structures, and provide an estimate of linear growth rate which characterizes the growth of auroral arcs.

In the previous theoretical analysis, however, effects of the magnetic curvature have not been fully considered while the dipole configuration was introduced. In this study, we discuss the effects of magnetic geometry on the feedback instability revisited. We have noticed three points on this issue. (1) An anisotropic property in the latitudinal and longitudinal directions appears due to the magnetic curvature. (2) Finite pressure gradient lead to coupling with the pressure gradient driven instability if a bad curvature region exists. (3) Direction of propagation of the most unstable mode may be influenced by the magnetic drift of electrons in case with kinetic effects.

In the presentation, we would like to mainly discuss the items (1) and (3) by means of the fluid and kinetic models.

静穏時オーロラの自発的成長を説明する理論モデルとして、磁気圏－電離圏結合系におけるフィードバック不安定性が考えられてきた。この機構は、オーロラアークにともなう局所電流系の形成や電子密度の増大をうまく説明するとともに、オーロラアーク成長を特徴づける線形成長率の見積もりを与える。

一方、これまでの理論解析では、双極子磁場形状は考慮されつつも、その曲率効果による影響はあまり考慮されてこなかった。本研究では、フィードバック不安定性理論を再訪し、磁場形状効果がもたらす影響について考察する。ここでは、主に 3 つの点が考えられる。(1) 磁場の曲率方向が生じるため、経度と緯度方向について異方性が生じる。次に、(2) 有限圧力勾配が存在すると、曲率の悪い領域がある場合、圧力駆動型の不安定性と結合する可能性がある。また、(3) 運動論的効果を取り入れると、電子の磁場ドリフト効果により最も不安定なモードの伝播方向が影響を受ける。

講演では、上記 (1) および (3) の効果について、流体および運動論的モデルを用いて議論する。

A hybrid simulation on three-dimensional structure of magnetotail reconnection region

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Recent Geotail statistical survey on the structure of the magnetotail reconnection region reveals that clear dawn-dusk asymmetry in the ion in/out-flow structure around the X-lines is identified. Particularly, the ion flow structure shows a remarkable edge effect on the dusk-side, while no clear edge effect is found on the dawn-side. In order to address what collisionless plasma physics would be taking place at the edges, we are carrying out a three-dimensional hybrid simulation on the magnetotail reconnection. In this paper, we will introduce observational facts and initial results of the numerical simulation.

THEMIS 衛星による昼側磁気圏境界面における磁束ロープの運動の観測

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Motion of a magnetic flux rope at the dayside magnetopause observed by the THEMIS spacecraft

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We investigate the motion of a magnetic flux rope observed at the dayside magnetopause, based on plasma and magnetic field data from the THEMIS spacecraft. Flux ropes observed at the magnetopause are generated by time-dependent magnetic reconnection in the presence of multiple reconnection X-lines. Since these structures have a large spatial scale, with a dimension comparable to one Earth radius, it is possible to analyze the structure and motion of the flux ropes by multi-spacecraft measurements. We analyzed the data taken by the THEMIS-A, -D, and -E spacecraft on June 24, 2015 when they observed a flux rope at the dayside magnetopause. Flux ropes are characterized by an enhancement of the total pressure of order a few nPa, polarity reversal of the ion flow velocity component parallel to the boundary surface, and bipolar change of the normal component of the magnetic field. We determined the velocity of the flux rope using multi-spacecraft timing analysis, under the assumptions that the observed flux rope was two-dimensional and moved at a constant velocity. We found that the flux rope moved dawnward at a speed of about 50 km/s, and its axis was roughly parallel to the GSM z axis. We discuss effects of the IMF orientation and geomagnetic dipole tilt on the dayside magnetopause reconnection.

THEMIS 衛星観測データに基づいて、地球磁気圏の昼側境界面における磁束ロープの移動過程を調べた。磁気圏境界面で観測される磁束ロープは、複数のリコネクションポイントを伴う非定常な磁気リコネクションによって形成されるが、地球半径程度の大きな構造のため、多点観測によってその構造や移動過程を明らかにできる。THEMIS 衛星は、2015年現在、A 機、D 機、E 機の 3 機で編隊観測をしている。磁束ロープの特徴として、磁気圏界面の電流層における磁場圧、プラズマ圧の和である全圧の数 nPa の上昇、境界面平行方向のイオン流速の極性の逆転、境界面法線方向の磁場成分の逆転などが挙げられる。2015 年 6 月 24 日に THEMIS 衛星によって観測された低エネルギーイオン及び磁場データから、3 機ともこれらの特徴が見いだされた。さらに、上記の特徴から各衛星が磁束ロープの中心付近を観測した時刻を求め、磁束ロープが二次元構造を維持して一定速度で移動していると仮定して、磁束ロープの移動速度を求めた。その結果、本イベントでは朝側に向かって約 50 km/s で移動していること、磁束ロープの軸は GSM 座標の Z 軸とほぼ平行であることが分かった。発表では、観測された磁束ロープの構造や運動に対する、IMF の向きや地磁気双極子の傾きの影響についても議論する。

Geotail observations of dayside magnetopause reconnection I

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On 06 July 2013, Geotail observed the dayside magnetopause reconnection for a long time period. In the period 0000-0800 UT on 06 July 2013, the solar wind has an almost constant speed of 350 km/s and the Interplanetary Magnetic Field (IMF) is almost southward, having a value of (0.0, +4.5, -12.0 nT). Geotail traveled from the magnetosheath to the magnetosphere. The Geotail position is (Xgsm, Ygsm, Zgsm) = (9.72, -2.23, -0.49 Re) at 0400 UT and (8.91, 0.87, -1.73) at 0600 UT, respectively. Geotail stays in the vicinity of the magnetopause, almost in the front magnetosphere. Reconnection jets with a speed of 200 km/s are observed near the reversal of the magnetic field. The reconnection jets flow northward, indicating that the reconnection site is located south of the Geotail position. There are two cases in the magnetic field variations. In most cases, the Bz magnetic field component is dominant and the field reverses from southward to northward in the crossing into the magnetosphere, and the reconnection jets are almost field-aligned. However, the magnetic field becomes almost perpendicular to the north-south direction, and the positive By magnetic field component is dominant. The reconnection jets are convection flows. In this study, the magnetic field topology and its relationship to the jets are investigated.

Geotail observations of dayside magnetopause reconnection II

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Plasma velocity distributions perpendicular to the magnetic field are generally isotropic by Larmor motion of ions and electrons. In actuality, isotropic velocity distributions are observed by Geotail. However, anisotropic ion velocity distributions were observed in the magnetosheath nearby the magnetopause when Geotail crossed the dayside magnetopause and observed ion flow jets by magnetic reconnection. The Geotail data of ion Energy-Time spectrogram on July 6, 2013 indicate anisotropic velocity distributions of ions energies higher than 20 keV at 0330 UT. The Geotail orbit is from magnetosheath through the magnetopause to the magnetosphere. The spacecraft GSM coordinates at the time of anisotropic ion velocity distribution observation are (9.8, 3.0, -0.2)R_E. This Geotail position is in the magnetosheath nearby the magnetopause. Ion energies are about 1 keV in the distant magnetosheath from the magnetopause. There are no ions with energies higher than 10 keV in the magnetosheath. There are ions with energies higher than 20 keV in magnetosphere. Thus, these ions are considered to go out toward the magnetosheath from the magnetosphere. We explain anisotropic ion velocity distributions by reconnecting magnetic field geometry.

高速電子フローを伴う磁気圏昼側リコネクションイベントの解析と粒子シミュレーションの比較研究

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Comparative study of an event of the dayside magnetic reconnection with high-speed electron flow and a full particle simulation

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The magnetic reconnection at the dayside magnetopause is asymmetric reconnection, where upstream physical quantities from magnetosheath and magnetosphere are different. Observation of dayside magnetic reconnection is useful when discussing processes of the energy conversion in the magnetic reconnection. We have analyzed a event of the dayside magnetic reconnection observed by THEMIS probes. We found wide plasma-outflow structure, where ions and electrons are not decoupled. We further discovered narrow high-speed electron flow channel along the magnetic field line at the boundary of the magnetosphere and the plasma-outflow region. This electron flow is close to Alfve'n velocity of the magnetosphere, and it seems to be accelerated at the X-line of the magnetic reconnection.

We have performed a full particle simulation of asymmetric magnetic reconnection by using 2.5-dimensional PIC code, for comparison. An initial condition of structures such as magnetic field, particle density, and particle temperature based on the observation are used. The simulated magnetic field, density, temperature and plasma outflow structure of the asymmetric magnetic reconnection are very similar to those of the observation. The narrow high-speed electron outflow structure similar to the observation is also produced at the boundary of the magnetosphere and the current sheet in the simulation. Electrons come from the magnetosheath region to the reconnection region, and are accelerated when passing the X-line. We have confirmed that the accelerated electrons form the outflow. This result indicates that the high-speed electron outflow at the dayside reconnection has physical information of the energy conversion at the electron diffusion region.

磁気圏昼側の磁気圏境界面で発生する磁気リコネクションは、リコネクション上流の物理量が太陽風由来と磁気圏由来とで異なる非対称磁気リコネクションである。磁気圏昼側の磁気リコネクションの観測は、磁気リコネクションにおけるエネルギー変換過程を議論する上で非常に有用である。今回は、THEMIS 衛星によって観測された昼側磁気リコネクションイベントの解析を行った。その結果、磁場が反転する領域で、イオンと電子が結合した広いプラズマアウトフロー構造を発見した。さらに、そのアウトフロー領域と磁気圏の境界で、磁力線に沿った狭い高速の電子フロー構造が見出された。この電子フローは、磁気圏のアルフベン速度に近く、磁気リコネクションの X-line 付近で加速されていることが示唆された。

観測との比較のために、2.5 次元 PIC コードを用いて非対称磁気リコネクションのシミュレーションを行った。初期条件として、観測を模した磁場・粒子密度・温度構造を採用した。その結果、衛星観測と非常によく似た非対称磁気リコネクション時の磁場・密度・温度・プラズマアウトフローの空間構造が再現された。さらに、観測と同様な高速の電子アウトフローが電流層と磁気圏の境界付近に生じた。この電子アウトフローは、磁気圏シース側から流入してリコネクションの X-line 付近を通過する電子が加速・加熱されて生成されたものであることが確認された。これは、昼側磁気リコネクションの電子アウトフローが X-line 付近の電子磁気拡散領域におけるエネルギー変換の物理的情報を保持していることを意味する。

レベルセット法を用いた脈動オーロラパッチの自動抽出

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Automatic extraction of pulsating auroral patches by using the level set method

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Pulsating aurora is a kind of aurora showing a quasi-periodic (several to tens of seconds) variation of the brightness and a patchy structure with a small spatial scale (less than several tens of km). It has been proposed that pulsating aurora is caused by pitch angle scattering through wave-particle interaction in the magnetosphere as a possible generation mechanism. However, the detailed mechanism is still open, due to lack of sufficient statistical analysis for pulsating aurora. It is difficult to perform statistical analysis of pulsating aurora, because pulsating auroral patches show various variations of the repetition period of brightness and contain patchy structures. Usually, the extraction of a pulsating aurora patch has been visually confirmed by researchers. In this study, in order to perform the statistical analysis of pulsating aurora, we have developed an automatic extraction technique of pulsating auroral patches by using the level set method, which is a kind of optimization method for moving object extraction. The observed auroral data used high frame rate all-sky EMCCD images (110 Hz sampling and spatial resolution 128 times 128 pixels with 4 times 4 binning) observed at Athabasca in Canada. To apply the level set method, the original aurora movie is separated into two types by using FFT analysis. One is a movie showing a slow variation (less than 20 sec) of optical emissions and the other is a faster one. The level set method is performed on the faster auroral movie to reduce the effect of diffuse aurora, which usually exists as a background for pulsating aurora. Additionally, we use a judgement criteria that the repetition period is less than 10 sec and the spatial velocity is less than several hundred m/s to classify whether the extracted patch is newly appeared or not. From these techniques, we can automatically detect pulsating auroral patches shown in all sky images. In this presentation, we will report our automatic extraction technique in detail.

脈動オーロラは、数秒〜数十秒の明滅周期をもち、比較的小規模な空間スケール（数十 km 程度）のパッチ形状をもつオーロラである。この脈動オーロラの発生メカニズムとして、磁気圏での波動粒子相互作用に伴う高エネルギー粒子（数 keV〜100 keV）のピッチ角散乱が示唆されている。しかし、脈動オーロラの統計解析が十分に行われていないため、その発生メカニズムは十分に理解されていない。脈動オーロラの統計解析を困難にする理由として、脈動オーロラのもつ多様な輝度値の周期性およびパッチ形状の変化のために、イベントの抽出は解析者の目視によって行われていることがある。そこで、我々は脈動オーロラの統計的性質を明らかにするために、動画像処理技術を用いて脈動オーロラパッチの自動抽出法を開発している。観測データは、サブオーロラ帯に位置するアサバスカ（カナダ）に設置された全天 EMCCD のデータ（サンプリング 110 Hz, 解像度 128∗128 ピクセル, 4∗4 ビニング）を用いた。全天に広がり異なる時空間変化を有する複数の脈動オーロラパッチの検出は、単純な画像の閾値処理では困難な場合が多い。我々はこの問題を解決するために、主に医療用画像の動オブジェクト抽出で使われているレベルセット法を適用した。レベルセット法は、動的に輪郭を変化させて輪郭抽出の最適化を行う形状最適化手法の一つである。このレベルセット法を適用させるために、まずオリジナルのオーロラ動画の各画素の輝度値の時間変化を周波数解析し、輝度値の時間変化の遅い（20 秒以上）成分と時間変化の速い成分の動画に分離した。これにより、輝度値の時間変化の速い（20 秒以下）成分で構成される動画にレベルセット法を適用させることで、脈動オーロラの背景に通常存在するディフューズオーロラの影響を低減している。さらに、脈動オーロラパッチは明滅を繰り返すため、消光後から増光に再び転じる際に同一のパッチか新しいパッチが形成されたのか判断が必要になる。この判断には、脈動オーロラの典型的な脈動周期（10 秒以下）と空間移動量（数百 m/s）を判断基準として、同一パッチの明滅なのか、新しいパッチが存在したのかを判別している。本発表では、我々が開発している脈動オーロラの自動検出法について詳細に報告する予定である。

Pre-flight tests of Medium Energy Particle analysers (MEPs) for ERG

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ERG (Exploration of energization and Radiation in Geospace) is geospace exploration spacecraft, which is planned to be launched in FY2016. 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 the medium-energy range (10-200 keV), since these particles 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. Proto-flight models (PFMs) of the medium-energy electron analyser and ion mass spectrometer have been fabricated and their environmental/performance tests are on-going. We report the latest results of these pre-flight tests.

VLF波動の伝搬ベクトル推定手法の改良と評価

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Improvement and Evaluation of Direction Finding Method for VLF Waves

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Investigating characteristics of plasma waves observed by scientific satellites in the Earth's magnetosphere and plasmasphere 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 plasma waves is most important for understanding these characteristics.

The wave distribution function (WDF) method was proposed for VLF waves in the Earth's magnetosphere/plasmasphere [1]. This method assumes that the observed signals are combinations of a continuum of superposed plane waves of different frequencies, propagating in different directions with no mutual phase coherence. In addition, this method also assumes that the observed signals are stationary and follow ergodic Gaussian random process with zero mean. Under these assumptions, the WDF method can estimate a WDF as directional distribution of wave energy density by using a spectral matrix which composes by cross spectra of observed signals. The WDF method is preferred when a wave source does not satisfy the plane-wave approximation or when it is widely extended. However, the WDF estimation is ill-posed problem, that is, the solution is not determined uniquely. Models as additional information for WDF must be needed to determine the solution uniquely. Many models have been proposed until now such as the Gaussian distribution model, and Markov random field model [2]. The estimation using these models works well if the sample number of observed signals is large enough to calculate spectral matrices exactly. Actually the number of sample observed by satellites is very few. We therefore must take into account that the spectral matrix which can be used for WDF estimation contains uncertainty.

To treat the uncertainty, we used the Bayesian inference, and we introduced probability density distribution which determines relationship between observed and theoretical spectral matrices. This introduction makes the WDF estimation enable to take into account the effect of sample number. We also studied Markov chain Monte Carlo (MCMC) methods as a Bayesian inference method for WDF estimation. Variational Bayesian method is also well known as a Bayesian inference method for complicated probability model. In this method, we need to get a proper class of approximate probability distribution. However, we cannot get it due to the complexity of probability distribution we set. We therefore must select MCMC methods, and evaluated the reliability and efficiency. Finally, we considered issues about the WDF method on the basis of results obtained by applying it to real data.

地球磁気圏及びプラズマ圏内の科学衛星で観測されるプラズマ波動の特性調査は, 波動の伝搬機構だけでなく, その励起・伝搬条件に関わるプラズマ環境を知る上で重要である. 特にプラズマ波動の到来方向は, これらの特性理解のために極めて有用な情報である.

磁気圏及びプラズマ圏内 VLF 波動の到来方向推定のために波動分布関数 (WDF) 法が提案されている [1]. この手法は, 衛星で観測される信号が異なる周波数, 到来方向でインコヒーレントな平面波の重ね合わせとして表されるとみなす. また, 観測信号は, 平均が 0 の定常ガウス過程に従うという仮定が課される. WDF 法では電場, 磁場成分を含む観測信号のクロススペクトルにより構成されるスペクトルマトリクスを用いて, 波動のエネルギー密度の到来方向分布 (WDF) を得る. WDF 法は, 観測信号が平面波近似を満たさない波動や, 広がった波源の到来方向推定手法として有用であるが, 不良設定逆問題であるため情報を付加する何らかのモデルを仮定し, 推定像を一意に定める必要がある. 現在までにガウス分布モデルやマルコフ確率場モデルなど幾つかのモデルが提案されており, スペクトルマトリクスの計算に十分なサンプル数を用いることのできる場合には良好な推定が可能である. しかし, 実際には衛星観測で得られるサンプル数は非常に少数であるため, 推定にはその不確実性を考慮する必要がある. 本研究では, この問題をベイズ推定により適切に取り扱い, 理論的に導出されるスペクトルマトリクスと実測値との関係を示す確率分布を定義した. この確率分布はサンプル数を陽に取り扱うことができる. また, 複雑な確率モデルのモデルパラメータ推定においては, 変分ベイズ法とサンプリング法が良く知られている. 本研究で扱う確率モデルの場合には変分ベイズ法の適用の際に必要となる適切な近似事後分布形が定められないため, 推定像の信頼性の観点からサンプリング法 [3] の適用を検討した. 特にサンプリング法の一種であるマルコフ連鎖モンテカルロ法 [3] を用いたモデルパラメータ推定の信頼性と計算効率についての評価を行った. 最後に, WDF 法を実観測データに適用し得られた推定結果から, 手法の課題について考察する.

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プラズマ波動観測用チョッパー ASIC プリアンプによるフリッカ雑音の低減

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Reduction of flicker noise using a chopper ASIC preamplifier for plasma wave observations

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Plasma wave observations by miniaturized satellites in the magnetosphere are important to understand the magnetospheric dynamics. We have been studying the miniaturization of the plasma wave instruments 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 reduce flicker noise of the previous ASIC preamplifier, we have developed a chopper stabilized ASIC preamplifier. Chopper stabilization technique is able to considerably improve the flicker noise (less than 1 kHz). The input voltage noise of the chopper stabilized ASIC preamplifier is by 20dB (at 1Hz) lower than that of the previous ASIC preamplifier. Thus, it is expected that magnetic field measurements in low frequency (e.g. ion cyclotron waves) are improved.

The noise sources of an operational amplifier consist of two parts: one is thermal noise dominated in high frequency band (more than 1 kHz), and the other is flicker noise dominated in low frequency band. The noise equivalent magnetic induction (NEMI) of typical magnetic sensors in low frequency is determined by flicker noise. The previous ASIC preamplifier consists of large gate area of transistors to decrease the flicker noise. In the chopper ASIC amplifier, the input signal is upconverted to a higher frequency in the thermal noise region. Then, the signal and the noise of the preamplifier are amplified. The signal is downconverted to the original frequency band. meanwhile the flicker noise is for then upconverted to the high frequency band. The prototype chopper ASIC preamplifier is current detection type. It is possible that the circuit has a differential input without a magnetic feedback. In comparison with the circuit of the previous ASIC preamplifier, the chopper ASIC preamplifier is complicated by including digital components. However it can reduce the chip area of ASIC.

We will present the design principles of our chopper ASIC preamplifier and discuss its electrical performances in detail.

磁気圏のプラズマ波動ダイナミクスを捉えるために超小型衛星の開発が進められており、それに伴い搭載されるプラズマ波動観測器の小型化も重要となっている。我々はアナログ ASIC(特定用途向け集積回路) 技術を用いて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 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、従来の ASIC プリアンプのフリッカ雑音を改善するためにチョッパースタビラリゼーションを用いて、チョッパー ASIC プリアンプの開発を行っている。チョッパースタビラリゼーションはフリッカ雑音 (1 kHz 以下）を大幅に改善することができる方式であり、入力換算雑音が 1 Hz で約 20 dB の改善を見込んでいる。これによりイオンサイクロトロン波などの低周波領域での磁界観測の改善が期待できる。また ASIC 化によりワンチップに収めることで小型化・低消費電力化 (14 mW) を実現することもできる。

通常のオペアンプは周波数に反比例する特性を持つフリッカ雑音領域とフラットな周波数特性をもつ熱雑音領域の二つの領域があり、低周波ではフリッカ雑音が支配的で観測感度は高周波 (1 kHz 以上) よりも低周波帯域で一般的に悪くなる。従来の交流磁界用 ASIC プリアンプはトランジスタのゲート面積を大きくすることでフリッカ雑音を抑制した。チョッパースタビラリゼーションは、入力信号をクロック周波数を用いて変調し、熱雑音領域で増幅することによりフリッカ雑音の影響を大幅に低減できる。プリアンプに含まれるフリッカ雑音は復調する際にクロック周波数で高周波帯域に遷移され、増幅された信号は復調により元の信号の周波数帯域に復元される。今回試作したチョッパー ASIC プリアンプは電流検出方式になっており、磁気フィードバックを必要とせず差動入力で構成できるメリットがある。従来の交流磁界用 ASIC プリアンプと比べて変調機構などのデジタル部を含むことにより回路は複雑化するが、トランジスタのゲート面積を大きくする必要がないために小型化に有利である。

本発表では、我々の開発しているチョッパー 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。

Propagation Pattern of Omega Signals Observed byPoynting Flux Analyzer Onboard Akebono

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To observe the Earth’s magnetosphere and plasmasphere, Japan has launched a satellite nicknamed Akebono (EXOS-D) in 1989. The PFX subsystem onboard of Akebono has been observing omega signal that was transmitted by 8 ground stations of omega system around 1989-1997 and is valuable for study about propagation characteristics of VLF waves in the ionosphere and plasmasphere. To analyze these signals, we are using automatic detection methods by developing an analyzer software. For the methods itself it consist of FFT analyses, determination of the stations which transmitted the signals, estimation of delay time, discrimination of signal existence and estimation of signal intensity. We also added some error detection and efficiency processing method for fast analyzing process. The result of intensity, delay time, and local time dependence analyses are presented in geographic and geomagnetic map.

After analyzing 2 years of PFX data from 1989 to 1990, we found that omega signals from each station have unique pattern propagation but they also have some common pattern. Latitudinal location of the station affects much of the propagation, that is, signals from the stations at higher latitude will show very wide propagation with large intensity, while signals from the stations at lower latitude show very narrow propagation with weak intensity. We also found that the signal become more electrostatic it propagates wider and further to the other hemisphere from the original transmission station. The omega system was operated until 1997, so that the PFX data obtained from 1991-1997 is available for further statistical analysis and it is now under study.

プラズマ波動観測器搭載用スペクトルマトリクス演算FPGAモジュールの開発

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Development of a FPGA module of spectral matrix calculator for plasma wave instruments

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In recent years, measurement of plasma waveform is essential for the study of solar-terrestrial plasma physics. As total amount of the waveform data is enormous compared to telemetry capacity, it is necessary to process and reduce the data onboard. Such a signal processing was conventionally performed by onboard CPU, but it was impossible to apply advanced signal processing in real time to all waveform data. In this study, we aim to realize a FPGA module that generates spectral matrix in real time.

We designed the module on a FPGA board peculiarly developed in our group for evaluation purpose of digital signal processing in plasma waveform receiver [1, 2]. Six components of waveform less than 20 kHz can be fed into the FPGA board. Two FPGA (FPGA#1 and FPGA#2) is mounted on the board. FPGA#1 is used for arbitrary signal generator, while FPGA#2 is the data processing unit to emulate plasma waveform receiver.

The FPGA module of spectral matrix calculator consists of three sub-modules, FFTModule and SeparatorModule and MatrixGeneratorModule performs a complex FFT on the waveform data. In the process of complex FFT, two channels of waveforms are simultaneously fed to the module, one channel to the real part and another one to the imaginary part. The SeparatorModule works to divide the obtained spectra into two channels again in the frequency domain. Finally these data are fed to the MatrixGeneratorModule and spectral matrix with 6 x 6 components is generated.

According to our theoretical evaluation, the developed module is fast enough to generate spectral matrix in real-time.

[1] Matsui et al., SGEPSS Fall Meeting #136, R006-P007, 2014.
[2] Kasahara et al., JPGU 2015, PCG31-19, 2015.

近年の科学衛星搭載のプラズマ波動観測器で生成される生の電磁界波形データは，衛星のテレメトリ伝送容量に比べて膨大なため，限られたリソースで最大の科学成果を得るための機上信号処理が不可欠である．従来，これらの信号処理はオンボードCPUが担っていたが，高度な信号処理をリアルタイムに全波形データに適用することは不可能であった．本研究では，FPGA(Field Programmable Gate Array) 上で，波動の到来方向推定に必要なスペクトルマトリクスの生成をリアルタイムに行える演算モジュールの実現を目指す．

信号処理モジュールの開発は，研究室で開発した評価用FPGAボードを使用する [1,2]．このFPGAボードは，衛星上で20kHz以下の電磁界波形を最大6成分の観測することを前提に設計されており，評価用に擬似信号を送出するFPGA#1と，実際に機上で観測波形データを処理するためのデータ処理部を想定したFPGA#2の2つのFPGAが搭載されている．それぞれのFPGAには外部RAMとしてDDR2メモリが接続されており，それぞれ評価用の擬似波形データの格納と処理後データの格納に用いることができる．また，USBケーブルによってPCと接続することで，付属のCPUを介して各FPGAと通信が可能である．ハードウェア記述言語にはVerilogHDLを使用した．

スペクトルマトリクスの計算では，取得した6成分の波形データに対して複素FFTを行い，これらの自己および相互パワースペクトルで構成された6x6の行列を作成し，それらの時間平均を求める．これを周波数成分の数だけ計算する必要があるが，スペクトルマトリクスがエルミート行列である特性を生かし，実際には対角成分と上三角成分のみを計算する．また，電磁界6成分を独立に6回複素FFTを行う代わりに，実部と虚部に異なる成分を代入して複素FFTを行い，得られた結果を再びそれぞれの成分に分離する方法を採用した．

現在開発中のモジュールは大きく3つに分かれており，複素FFTを行うFFTModule，2成分同時に実施した複素FFTの結果を，各成分に分離するSeparatorModule，スペクトルマトリクスを計算するMatrixGeneratorModuleで構成されている．複素FFTは1フレーム512sampleで行うことを想定しており，FFTModule及びSeparatorModuleは3並列，MatrixGeneratorModuleは一度に対角成分と上三角成分の最大21要素を演算することを想定している．評価用FPGAボードでは，サンプリング周波数を65536[Hz]としており，512sampleのデータを処理する場合，リアルタイム処理可能な最悪処理時間は512/65535=7.8[ms]である．動作クロックを25[MHz]とした時のFFTModule及び，SeparatorModuleのシミュレーションにおける処理時間はそれぞれ0.51[ms]，0.041[ms]である．MatrixGeneratorModuleの処理は1要素の演算に2cycleかかると仮定し，それらを256回繰り返し，6回分の時間平均を求めると想定すると，0.123[ms]で，これらすべてを合計しても十分リアルタイム処理が可能な計算量であることを確認した．またこれらの演算に必要なFPGAの大きさはCyclone IV Eの10〜15%程度であり，回路規模的にも十分小さいモジュールで構成できることを確認した．現在，桁あふれ処理などの実装を行っており，今後，同モジュールを実機上で動作させ，その性能を定量的に評価を行う予定である．

[1] 松井 他, SGEPSS 第136回総会及び講演会, R006-P007, 2014.
[2] 笠原 他, JPGU2015年大会, PCG31-19, 2015.

あけぼの衛星で観測されたコーラスのエレメント形状の統計処理のための自動抽出法

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Automatic extraction of features of chorus elements observed by Akebono

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Statistical analysis of relations between waves with rising tone frequencies and ambient plasma plays an important role to study wave-particle interaction. Chorus emission is one of such waves. In order to quantify features of chorus elements, we developed an automatic extraction method which is based on a modified template matching. One of the essential modifications is that intensity distribution of the template is determined according to that of target chorus elements. We applied the method to the huge waveform dataset of Akebono to make a statistical analysis of the features of chorus elements. As a result, the features of plenty of chorus elements are successfully extracted.

非線形な波動粒子相互作用により，コーラスや VLF トリガードエミッションなど周波数の遷移を伴うプラズマ波動が励起される．このような波動と背景プラズマ（観測領域）との関連を実観測データにより統計的に調査するためには，大規模なデータセットから対象の波動現象を自動抽出することが不可欠である．1989 年に打ち上げられたあけぼの衛星は 26 年間という長期間に渡り観測を続け，2015 年 4 月に運用を終了した．搭載機器の一つであるＷＢＡ（Wide-Band Analyzer:広帯域ＶＬＦ波動受信器）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，数 10 TB という大容量のデータとして蓄積されている．本研究では波動現象の中でもライジングトーンコーラスを対象として，テンプレートマッチングによる自動抽出を試みた．

コーラスは，スペクトログラム上で周波数の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変化率，継続時間は生成・伝搬過程に依存している．このコーラスの特徴を定量化するために，スペクトログラムを対象画像，コーラスのエレメントを模擬した画像をテンプレート画像，類似度を相互相関係数としてテンプレートマッチングを行った．コーラスエレメントに対するテンプレートマッチングは従来から行われてきたが，エレメント内の強度分布の多様さをテンプレートマッチングで表現できないという本質的な問題があり，有意な類似度に基づき純粋に機械的な抽出を行ったという例は見られない．この問題に対して，本研究ではテンプレートの強度分布とマッチさせるエレメントと同一の強度分布になるようにすることで解決した．すなわち，テンプレートの強度値をあらかじめ用意せず，類似度を計算する際に切り出したスペクトログラムの強度値を並び替えてその都度，決定するようにした．スペクトログラムを走査するたびにテンプレートの強度値を決定することから，多大な計算時間を必要とするが，コーラスの抽出性能が格段に向上したことから手作業での後処理が不要となり，結果的に処理効率が向上した．これを基に，あけぼのの大容量の波形データから抽出されたコーラスのエレメントに対して周波数変化率および継続時間の各種パラメータ依存性を統計処理した結果について報告する．

将来磁気圏探査に向けたX線望遠鏡の設計

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Design of an X-ray telescope for imaging of the Earth’s magnetosphere

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We are developing an ultra-lightweight X-ray telescope using MEMS (Micro Electro Mechanical Systems) technologies towards the next generation small satellite GEO-X. It aims to take global X-ray images of the Earth’s magnetosphere for the first time. In this study, we report on our design study of the X-ray telescope using a raytracing simulation.

我々のチームでは、世界初の地球磁気圏の X 線画像の取得を目指す次世代型小型衛星 GEO-X に向けて、MEMS (Micro Electro Mechanical Systems) 技術を用いた超軽量 X 線望遠鏡 (Ezoe et al. 2010 MST) の製作を行っている。我々は MEMSX 線望遠鏡の ray tracing プログラムを構築し、ミッション要求を満たす基本設計を行った。本講演では、その成果について報告する。

MEMSX 線光学系とは、マイクロマシン技術により Si 基板に微細かつ垂直な曲面穴を無数に形成し、穴の側壁を反射鏡として用いる超軽量次世代 X 線光学系である。GEO-X のミッション要求は、エネルギー帯域は 0.3–2 keV、角分解能は <9 分角、S Ωは 0.6 keV において >10 cm^2 deg^2、視野は望遠鏡あたり 1.8 deg ∗1.8 deg 以上である。現在の光学系の設計は、製作実績に基づき、Si 基板の厚み 0.3 mm、穴幅 0.02 mm、開口率 約 33 %であり、基板の危局率半径が、 1 段目 1000 mm 2 段目 333 mm である。要求のうち角度分解能は製作時の鏡の状況や配置制度で決まり、エネルギー帯域や視野は鏡の粗さと焦点距離によって制限される。これらは製作時の表面形状や解析的計算で見積もることが可能だが、一方で S Ωは非光軸からの入射に対する応答を考慮する必要があり、解析的に解くことが困難である。そこで要求を満たすか、ray tracing を用いて調べた。結果は、Ir コーティングした Si 基板を用いると 0.6 keV で 14.8 cm^2 deg^2 となり、要求を満たすことがわかった。また、最適な基板厚みを知るため、S Ωの基板厚み依存を調べた所、基板厚みを 0.1~1 mm の範囲で振った結果、S Ωは基板厚み 0.5 mm で最大となり、45 %程度の増加が見込めることが分かった。本講演では、S Ωの結果を中心として、プログラムを用いた予想性能について述べる。

Evaluation of a statistical significance by wave data processing in the WPIA

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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. In order to statistically evaluate the significance of the quantity of energy transfer, the WPIA require accurate phase angles of waves and electrons. In the WPIA, the waveform data over a wide frequency range is observed by electric and magnetic sensors on the satellite and the data is used as input of WPIA processing. To obtain chorus waves, the WPIA processing applies a passband filter with appropriate frequency range of the waveform. Additionally, the chorus emissions often appear with weak hiss-like waves in the same frequency band. Such waves give a decreasing of the S/N ratio for the WPIA calculation. In the presentation, we evaluate a statistical significance in the WPIA measurement depending on the passband filter useing chorus elemet reproduced in the simulation.