Hybrid simulations on the evolution of the pickup density structure associated with the fluctuating heliopause

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We have examined the pickup ion (PUI) dynamics influenced by the fluctuating heliopause by means of two-dimensional hybrid simulations. PUIs are provided in the outer heliosheath, where a charge exchange process takes place between the neutral solar wind and interstellar plasmas. The PUI column density integrated in the direction perpendicular to the heliopause implies the profile of energetic neutral atom (ENA) emission detected by IBEX. In this study, we investigated how the Kelvin-Helmholtz instability or magnetic reconnection affect the PUI density structure under various conditions in the vicinity of the heliopause. The characteristics of the resultant column density can associate the profiles from IBEX observations with the physical processes occurring around the heliopause. It is expected that the results will be used as a template for determining the environment of the heliospheric boundary region.

R007-02 **会場: E** **時間: 11 月 26 日 9:15-9:30**

太陽圏への銀河宇宙線の輸送過程の数値実験

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Numerical simulation of the transport process of galactic cosmic rays into the heliosphere

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Cosmic rays are highly energetic charged particles found almost everywhere in space. Although the majority of galactic cosmic rays (GCRs) are prevented from entering the heliosphere, some fraction of them can reach deep inside it and can be observed at the Earth. The heliosphere has two large scale discontinuities called the solar wind termination shock and the heliopause. The heliospheric magnetic field typically shows the Parker spiral structure and plays a dominant role in the transport process of GCRs Voyager spacecraft have explored in-situ the boundary region of the heliosphere. Further, large scale MHD simulations are also performed and detailed structures of the boundary region are being revealed. In this study, we investigate the transport process of GCRs into inside the heliosphere by performing test particle simulations using the electromagnetic fields produced by a global MHD simulation.

In the last meeting we reported the results of analysis on some typical orbits of test particles (protons) in the electromagnetic fields obtained from an MHD simulation in which a global heliosphere is reproduced by assuming the time stationary solar wind conditions. The following points are revealed. Most of lower energy (~10 GeV) particles go around the heliosphere along the draped interstellar magnetic fields or are mirror reflected so that only a few particles can enter the heliosphere. When particle energy becomes large (~1000 GeV), such particles can relatively easily enter the heliosphere since their gyroradii are in the same order of the size of the heliosphere.

In this study, we calculate motions of larger number of particles with sufficiently long time and investigate statistics of the particles which finally reach the inner boundary at 50 AU. As initial conditions, 1 million particles homogeneously distributed in the interstellar space far upstream of the heliosphere on the surface of 1/8 sphere at R = 500 AU. Their initial velocity distribution function is given by mono-energetic shell distribution. Sufficiently long time simulations with different particle energies from 10 GeV to 100TeV are performed and statistics of the particles finally reach the inner boundary is examined. It is found that the ratio of invading particles increases as their initial energy. The particles having relatively low energy (< a few 100 GeV) have higher probability of reaching the polar region, while the particles having middle energy (~1000 GeV) have higher probability of reaching the region of mid-latitude and mid-altitude. In the poster we will show the results of analysis on higher energy particles and, further, estimate energy distribution of particles outside the heliosphere.

地球に到達する銀河宇宙線は、例外的に太陽圏内部に侵入した宇宙線の一部である。太陽圏は、太陽から吹き出す超音速の太陽風プラズマと星間プラズマとの相互作用によって形成され、太陽風プラズマが超音速から亜音速に遷移する終端衝撃波や、星間プラズマとの接触不連続面である太陽圏界面と呼ばれる大規模境界構造が存在している。太陽圏内は太陽からのスパイラル磁場が支配しているため、太陽圏界面を通過して圏内に侵入した宇宙線の挙動はこれに影響される。現在ボイジャーによる太陽圏境界領域の直接探査が進行中であり、複雑な同領域の構造が観測的に明らかになりつつある。また大規模 MHD 計算により太陽圏の全体像についての理解も進んできている。本研究では、近年高精度化が進む大規模 MHD 計算とテスト粒子計算を組み合わせ、宇宙線の太陽圏への侵入過程の解明を目指す。

昨年の講演会では、定常太陽風を仮定した大規模 MHD 計算で得られた太陽圏の大規模電磁場構造を用いて、太陽圏外から侵入する銀河宇宙線のテスト粒子計算を行い、10・、100・、1000GeV の粒子の軌道を解析した。その結果、10GeV の粒子の大多数は星間磁場に沿って太陽圏を迂回するか、太陽圏の手前でミラー反射され、ごく一部の粒子だけが太陽圏内に侵入できること、1000GeV の粒子はジャイロ半径が太陽圏スケールと同程度になるため、比較的容易に太陽圏内部にまで侵入できることなどを示した。

本研究では、粒子数を増やし、十分長時間の計算を行って、内部境界（R=50AU）に到達した侵入粒子の統計について議論する。初期条件として、単一エネルギーをもつ粒子を 100 万個用意し、前回使用した電磁場構造内に配置した。その際、空間分布を太陽圏前面の R=500AU 地点の 1/8 球面上に一様に配置し、速度分布としてシェル分布を与えた。10GeV ～100TeV の範囲で粒子エネルギーを変えた十分長時間の計算を行い、内部境界まで到達した粒子数が一定に落ち着いた後でそれらの統計を調査した。内部境界への粒子の到達率はエネルギーとともに上昇した。到達粒子の緯度－経度分布を調べたところ、100GeV 程度以下の低エネルギーの粒子は極域に多く、1000GeV 程度の粒子は中緯度・中経度域に多く偏ることが分かった。発表では、さらに高エネルギーの粒子についての解析結果を報告するとともに、上記の結果及び実際に観測されている宇宙線のエネルギー分布から、星間空間でのエネルギー分布の推定を行う。

「ひさき」衛星光学観測による惑星間空間ヘリウムの分布

山崎 敦 [1]; 村上 豪 [2]; 吉岡 和夫 [3]; 木村 智樹 [4]; 土屋 史紀 [5]; 鍵谷 将人 [6]; 坂野井 健 [7]; 寺田 直樹 [8]; 笠羽 康正 [9]; 吉川 一朗 [10]
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Neutral helium distribution in interplanetary space by Hisaki observation

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The Hisaki (SPRINT-A) satellite has a main scientific topic of the planetary magnetspheic physics and atmospheric evoluiton by long-term observations, but carried out the non-planetary observation at the time when there is not observation oppotunity for planets. One of them is an observation of helium atom resonance scattering from interplanetary space.

A material in the interstellar medium (ISM) travels into the heliosphere over the heliopause due to the relative velocity between the heliosphere and interstellar gases. The helium atoms move into about 0.5Au of the neighboring from the sun without ionizing because of its high ionization energy. The helium atoms are bent by sun gravity along the Keplerian orbit and forms a high density region on the down wind side, which is called helium cone. The distribution of helium atoms in the helium cone can estimate the speed and direction of the interstellar wind, and the density and the temperature of the helium atom in interstellar gases. The interplanetary observation is one of tools to recognize the interstellar medium from inside the heliosphere.

This study was carried out from the 1970s, but the recent IBEX satellite observation results show that the interaction between the ISM and heliosphere. The Hisaki satellite carried out the observaiont of the resonance scattering from inside the helium cone during November and December of three years. In this presentation, the Hisaki's observation results of the helium cone in years of 2015 - 2017 are shown, and the features of the interstellar wind are reported.

名古屋多方向ミューオン計で観測された宇宙線強度の長周期変動

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Long-term variation of galactic cosmic ray intensity observed with the Nagoya multidirectional muon detector

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http://cosray.shinshu-u.ac.jp/crest/

We recently developed the method of the correction of the atmospheric temperature effect on muon count rate by using the GMDN (Global Muon Detector Network) data (R. R. S. Mendonca et al., Astrophys. J., 830:88, 2016). This is a significant step, because it makes possible for the first time the analysis of the long-term variation of ˜50 GeV cosmic ray density (i.e. isotropic intensity) which has been possible only for cosmic ray below ˜10 GeV using the neutron monitor data nearly free from the temperature effect. In this report, we report the 11-year and 22-year variations of cosmic ray density observed with Nagoya muon detector in 1970-2012 and discuss the energy dependence of variations by comparing the observation with the neutron monitor.

我々は、GMDN（Global Muon Detector Network）による観測データにもとづき、地表ミューオン強度に対する気温効果の補正法を開発した（R. R. S. Mendonca et al., Astrophys. J., 830:88, 2016）。本講演では、名古屋多方向ミューオン計による観測データ（1 次宇宙線の平均リジディティー〜50GV）を補正し、1970 − 2012 に観測された宇宙線強度を中性子計による観測（〜10GV）と比較することにより、11 年周期及び 22 年周期変動のエネルギー依存性について報告する。

Crab パルサーを用いた太陽コロナの電波掩蔽観測

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Radio observation of the Solar Corona from Occultation of the Crab Pulsar

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The Crab Pulsar (PSR B0531+21) is a relatively young neutron star located in the center of the Crab Nebula. The Crab emits broadband pulses with an emission interval of 33ms over a wide spectrum range from radio waves to gamma rays, and also occasionally emits extremely strong pulses called ’giant pulses’ with intensity 1000 times greater than the regular pulses. Counselman & Rankin (1972, 1973) and Weisberg et al. (1976) determined the mean electron density of the solar corona from measurements of radio-frequency dispersion measure (DM) for the Crab in mid-June, when the line-of-sight (los) of the Crab approaches to the Sun as close as 5 solar radii over the South pole. The DM is the integrated column density of free electrons between an observer and a pulsar, therefore one can determine the integrated coronal density by measuring the Crab’s DMs in mid-June.

We have observed the Crab using Solar Wind Imaging Facility Telescope (SWIFT) at the Toyokawa radio observatory since November 2016. The observation frequency of SWIFT is 327 MHz, and the effective area is 1970 m^2 (at zenith). In mid-June 2018, we conducted Crab observations for seven days to estimate the coronal density. As a result, we detected an increase of ˜0.01 pc cm^{-3} in DM on June 16 when the Crab’s los was closest to the sun. This DM increase is consistent with the integrated coronal density model along the los. Our data also showed relatively high pulse temporal broadening and low giant pulse detection number in the same period. These may suggest an increase in pulse scattering due to density fluctuations in the corona.

惑星間空間シンチレーション観測を用いた内部太陽圏の可視化と太陽嵐到来予測

岩井 一正 [1]; 塩田 大幸 [2]; 徳丸 宗利 [3]; 藤木 謙一 [4]; 田 光江 [2]; 久保 勇樹 [5]
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Visualization of the inner heliosphere and space weather forecasting using interplanetary scintillation observations

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Coronal mass ejections (CMEs) sometimes cause disturbances of the geospace which are closely related our life such as radio telecommunications, spacecraft and airplanes operations, and GPS navigations. Therefore, forecasting of CMEs has become more and more important. However, the prediction of the CME arrival is still difficult because the initial speed of CMEs derived from white light coronagraph observations has an ambiguity, and the acceleration and deceleration processes of CMEs propagating in the interplanetary space have not been understood well. An interplanetary scintillation (IPS) observation detects CMEs from the continuous ground-based radio observations. Institute for Space–Earth Environmental Research (ISEE), Nagoya University has operated radio telescopes dedicated to the IPS observation at 327 MHz, which can detect radio scintillation signals generated between 0.2 and 1.0 AU. On the other hand, it has been difficult for the IPS observation, which scans the inner heliosphere once a day, to detect fast CMEs. The purpose of this study is to develop a visualization system of the IPS observation data using MHD simulation to understand propagation processes of CMEs in the inner heliosphere and predict their arrival to the Earth. In our IPS data driven MHD simulation system, the initial speed of a CME is roughly derived from the white light coronagraph observations. Then, the propagation of the CME is calculated by the MHD simulation (SUSANOO-CME; Shiota and Kataoka 2016). An IPS amplitude of each radio source is calculated using the 3D electron density variation derived from the MHD simulation. Several calculated IPSs are compared with the observed IPS to evaluate the most accurate simulation result, which enables us to predict the arrival time the CME. We simulated the propagation of some CMEs observed in 2017 and succeeded to derive the calculated IPS that are close to the observed IPS.

太陽から放出されるコロナ質量放出（CME）現象は地球に到来すると地球周辺環境に擾乱をもたらし、電波通信や人工衛星・航空機の航行、GPS 測位など、社会生活に様々な影響を与えるため、到来前に予報することが重要である。しかし、可視光のコロナグラフ観測などから求まる CME の初期速度には誤差があることや、惑星間空間中を伝搬する過程で CME が加速・減速を受ける影響はまだはっきりと理解されていないことから、CME の到来予報はいまだ難しい課題である。惑星間空間シンチレーション（IPS）観測は、遠方天体の地上電波観測から CME の通過に伴う電波の散乱現象を捉えることで地球方向に飛来する CME を検出できる。名古屋大学で行っている IPS の観測周波数 327MHz では、0.2 から 1AU までの範囲に感度があり、伝搬途中の CME を検出しやすいという利点がある。一方、本観測は内部太陽圏を 1 日かけてスキャンするため、比較的時間変動の早い CME を追跡することは難しかった。本研究では CME の内部太陽圏における伝搬過程を理解し、地球への到来予報精度を向上させることを目的とし、磁気流体 (MHD) シミュレーションを用いた IPS 観測データの可視化システムを開発した。本システムでは、まず可視光のコロナグラフ観測から CME の初期速度を求め、MHD シミュレーション SUSANOO-CME(Shiota and Kataoka 2016) を用いて伝搬のシミュレーションを行う。そこで得られる内部太陽圏の 3 次元密度分布を元に、地球から各電波天体への視線に沿った電波の散乱を解くことで擬似的な IPS データを再現する。複数の CME 初期速度で計算し、それぞれから得られる擬似 IPS データの中から、最も実際の IPS 観測を再現する結果を採用することで予報精度の向上を可能とする。2017 年に発生した代表的な CME に対して本シミュレーションを行った結果、実際の IPS 観測に近い擬似 IPS データの再現に成功した。

Comparative Study of Microwave Polar Brightening, Polar Coronal Hole, and Polar Solar Wind

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Polar brightening of the Sun at 17 GHz observed with the Nobeyama radioheliograph shows a solar cycle dependence, brighter at a solar minimum and darker at a solar maximum. Also, it has been reported that the polar brightening highly correlates to polar magnetic field strength (r˜0.86). The plausible model to explain the cycle dependence of polar brightening is that a height scale of the solar atmosphere in the polar region depends on the solar cycle. Indeed, the polar region is covered by large coronal holes except for a short period during a solar maximum, and the size of the polar coronal hole depends on a solar cycle.

Motivated by these observational facts, we compare the polar brightening, polar coronal-hole size, and polar solar-wind speed from July 1992 to December 2017. The magnetic features in the polar regions are determined by using synoptic observation data obtained at Kitt Peak National Solar Observatory, coupling with a coronal magnetic field extrapolation technique. The solar-wind speed in the polar region is determined by using the interplanetary scintillation (IPS) observation at Nagoya University.

As results, we obtained the following results. 1) The distribution of polar brightening matches spatially and temporary to the probability distribution of coronal holes. 2) The brightness temperature of the polar brightening strongly correlates with the predicted size of the polar coronal hole (A); r˜0.95. 3) The solar wind speed (V) around the polar region highly correlates with the polar brightening; r˜0.81. From these results, we conclude that polar brightening reflects the coronal-hole area or magnetic flux expansion rate (f) in the polar region. Solar wind speed can be predicted by using the polar brightening, which is similar to the empirical relationships of A-V and f-V.

Generalization of constant-alpha force-free cylindrical flux rope model

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The interplanetary flux rope (IFR) is a transient magnetic field structure expelled from the Sun. The magnetic field structure of IFR consists of helical field lines whose pitch angles change with the distance from the axis. These properties are often compared with those at the Sun. For example, the tilt angle of the axis is compared with that of the magnetic polarity inversion line on the photosphere or the elongation direction of coronal mass ejection (Yurchyshyn et al., 2007; Marubashi et al., 2015). This comparison should help us to understand the dynamics of IFR propagation and lead to improvement of space weather forecasting. On the other hand, helical field lines relate to the poloidal magnetic flux inside the IFR and the magnetic flux is compared with that of the eruption region. This comparison gives us hint on how reconnection contributes to the formation of the poloidal magnetic flux of the flux rope at the Sun (Hu et al. 2014). Thus, understanding the axis orientation and helical field lines of IFR is important. IFR structure has been analyzed by many model fitting methods and reconstruction methods. A widely used model is the cylindrical constant-alpha force-free model (Burlaga, 1988; hereafter, we call it the traditional model). This model is based on the Lundquist solution and the pitch angle of the helical field line becomes 90 deg at the boundary. This boundary condition has been used since many IFRs show 180 deg rotation of observed magnetic field direction. However, IFRs exhibiting considerably small rotations of the magnetic field (for example less than 60 deg) are often observed suggesting that the pitch angle of the helical field line at the boundary may not be 90 deg. Therefore, we relax the restriction that the pitch angle should be 90 deg at the surface and try to fit the observational data to this generalized flux rope model. It can be done by taking the pitch angle at the surface as an additional free parameter in addition to the traditional model. It is known that this new model satisfies the force-free condition. The selection of the pitch angle at the boundary should affect the model fitting result; the structure of the helical field lines and the axis orientation. Therefore, it is expected that the new model changes our understanding of the relationship between IFRs and flux ropes at the Sun. In this presentation, we introduce the new model and show the difference between results from our new model and those from the traditional model. We analyze 87 magnetic obstacles (MOs) listed in Linkcat (https://www.helcats-fp7.eu/catalogues/wp4_cat.html) between 2008 and 2013. The term magnetic obstacle is introduced by Nieves-Chinchilla et al. 2018 in order to signify the possibility of more complex IFR configurations. Thus, MOs are allowed for departures from idealized IFR configurations. The new and traditional cylindrical models are fitted to in situ observations of MOs by Wind, STEREO-A or STEREO-B. 38 out of 87 MOs are fitted well using the new model (cf. 35 out of 87 MOs for the traditional model). The remaining MOs (49 out of 87 MOs) may not be structures suitable for cylindrical flux rope models; toroidal or highly distorted shape and so on. The difference of tilt angles between the new model and the traditional model is found to be small (less than 15 deg) except for one event. Therefore, the selection of the pitch angle at the boundary little affects tilt angles. However, the large difference of axis orientations (greater than 30 deg) is shown for about 30% events although the tilt angles are maintained. The pitch angle of the new model at the boundary significantly changed from that of the traditional model for the non-negligible number of events (about 40% events). The results show that the new cylindrical model should be taken into account especially in examining the helical field line structure of IFR.

太陽風磁気ロープの構造を解析するモデルの比較

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Comparison of Models for Analysis of Interplanetary Flux Rope Structures

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The interplanetary magnetic flux ropes (IFRs) have long been studied from the viewpoints that they are main drivers of strong (Dst < 100 nT) geomagnetic storms, and that they provide information on the generation mechanism of CMEs. It is a key problem in such studies to determine the 3-D geometries and the internal magnetic field structures of IFRs. In order to challenge the problem, we need to assume a model of the IFR and compare the model structure with observed magnetic fields in IFRs, because the in situ solar wind observations are made at a single point. Currently, the following three analysis methods are commonly used: (1) to compare the observations with models based on the force-free field configurations, (2) to assume appropriate electric current distribution without a force-free condition and compare the model fields with the observed fields, and (3) a method based on the Grad-Shafranov (GS) equation that is valid for 2-D magnetic field structure. The IFR properties obtained by these 3 methods do not completely agree, so far. Indeed, there are many IFR examples for which the 3 methods yield completely different geometries. Recently, Al-Haddad et al. (Solar Phys, 2018) examined the degree of mutual agreement between the results from the 3 methods for 13 simple IFRs carefully selected. Inspired by the work, we have decided to attempt to reconcile results from the force-free model and the GS reconstruction. The point is that the axial field is not zero at the surface of an IFR obtained from the GS method. In other words, the GS method cannot be applied to those IFRs which exhibit magnetic field rotations greater than 180 across the structure. On the contrary, the force-free model, in which it is commonly assumed that the axial field is zero at the surface, may not be appropriate to reproduce such IFRs for which the rotation angle are small. It is expected that a new model by Nishimura et al. (2018, presented in this SGEPSS meeting) gives better results. We attempt to inspect the above idea using the 13 IFRs selected by Al-Haddad et al.

太陽風磁気ロープ（IFR）は、強い磁気嵐（Dst < -100 nT）の駆動源として、また CME 発生機構の手がかりをあたえるものとして、広く関心をもたれている研究課題である。いずれの面からも、IFR の 3 次元形状と内部磁場構造を決めることが重要なカギである。太陽風磁場の観測からこの問題にとりくむには、IFR のモデルを仮定して観測と比較する手法が必要になる。現在、以下の３つの解析法が広く使われている：（１）force-free 磁場構造を仮定するモデルによる解析、（２）force-free を仮定せず、適当に仮定した電流分布による磁場と比較する解析、（３）2 次元的な磁場に適用される Grad-Shafranov（GS）方程式から磁場構造を構築する解析。これまでのところ、上記３つの方法で得られる IFR の形状、内部構造には完全な一致は見られない。特に３つの方法が完全に異なる形状を与える事例も数多く存在する。最近 Al-Haddad et al. (Solar Phys, 2018) は、できるだけ簡単な 13 の IFR を選び、３つの方法で得られる結果の一致度合を考察した。この論文に触発されわれわれは、force-free モデルと GS 方程式の結果を調和させることを試みる。ポイントは GS 方程式から得られる IFR 構造では、表面で軸方向の磁場が 0 にならないことである。言い換えれば、衛星が IFR を通過したときに観測される磁場ベクトルの回転が 180 以上になるような場合には GS 法は使えないことになる。逆に、回転角の小さい IFR の再現には、表面で軸方向磁場が 0 になることを仮定した従来の force-free モデルは不適当かも知れない。Nishimura et al. (2018, 本学会講演) が提案する 0 でない軸方向磁場をゆるす force-free モデルが正しい形状をあたえる可能性がある。この発表では Al-Haddad et al. の選んだ 13 の IFR について、上に述べた考えを検証する。

Parametric decay instability of Alfven waves in the solar wind

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Using numerical simulations we investigate the onset and suppression of parametric decay instability (PDI) in the solar wind, focusing on the suppression effect by the wind acceleration and expansion. Wave propagation and dissipation from the coronal base to 1 au is solved numerically in a self-consistent manner; we take into account the feedback of wave energy and pressure in the background. Monochromatic waves with various injection frequencies, f_0, are injected to discuss the suppression of PDI, while broadband waves are applied to compare the numerical results with observation. We find that high-frequency (larger than 10^{-3} Hz) Alfven waves are subject to PDI. Meanwhile, the maximum growth rate of the PDI of low-frequency (lower than 10^{-4} Hz) Alfven waves becomes negative due to acceleration and expansion effects. Medium-frequency (around $10^{-3.5}$ Hz) Alfven waves have a positive growth rate but do not show the signature of PDI up to 1 au because the growth rate is too small. The medium-frequency waves experience neither PDI nor reflection so they propagate through the solar wind most efficiently. The solar wind is shown to possess a frequency-filtering mechanism with respect to Alfven waves. The simulations with broadband waves indicate that the observed trend of the density fluctuation is well explained by the evolution of PDI while the observed cross-helicity evolution is in agreement with low-frequency wave propagation.

月の極域で観測された 1-12Hz の磁場変動の周波数降下について

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Falling-tone ELF magnetic fluctuations detected by Kaguya above the lunar polar region

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Falling tone magnetic fluctuations in a frequency range 1 to12 Hz were detected by MAP/LMAG onboard Kaguya at an altitude of 100 km above the moon. They were right-hand polarized, and the k vector was parallel to the background magnetic field. They were detected when the moon was in the Earth's magnetosheath and the spacecraft was moving along a path from the evening side toward the north pole of the moon. An attempt was made to explain the falling tone spectral feature with a cyclotron resonance of a whistler wave and ions sputtered from the moon.

月周辺には月と太陽風との相互作用によって様々な磁場変動が生じている。その多くは、月の固有磁場の上空や、磁力線によって固有磁場と衛星がつながれるときに観測される。固有磁場あるいはそこに生じる局在電場によって太陽風のプロトンや電子が効果的に反射されるためである。しかし、強い固有磁場の見られない月の北極域で、極に近づくにつれて周波数が下がってゆく特徴的な磁場変動が発見された。本発表ではこの周波数分散の成因について考察する。

この磁場変動は月が地球磁気圏のシース中にあった 2008 年 6 月 14 日、かぐや衛星が夕方側（地方時はおよそ 19 時）から月の北極に向かって飛行中に検出された。周波数降下のある磁場変動は３回連続して観測された。20:40 に 8Hz に現れた磁場変動の周波数が 7 分かけて 1Hz まで連続的に下り、次いで 20:47 に 10Hz に現れた磁場変動が 20:52 までに 1Hz に下がり、さらに 20:51 頃 12Hz に現れた磁場変動が 21:00 までに 1Hz まで降下し、21:00 に北極に衛星が達すると 1-12Hz 全域に磁場変動がみられ、そこで磁場変動は止まった。この期間中、背景磁場はほぼ南向きで、衛星と月面を最短距離でつないでいたが、磁力線の先の月面上には顕著な磁気異常はなかった。磁場変動の偏波方向は背景磁場に対してすべて右回りであった。Minimum variance analysis によって周波数ごとに求めた k ベクトルの方向は磁力線にほぼ平行であった。ACE 衛星観測によると太陽風速度は 500km/s, 密度は 20 個/cm^3 であった。

k ベクトルの方向が太陽風の方向に垂直なので太陽風によるドップラーシフトは考えなくてよく、偏波が右回りであることからこの波はホイスラ波と考えられる。この周波数帯では高周波は速く、低周波は遅く伝搬する。周波数変化が太陽風による移流であれば、昼へ向かう軌道では遅い低周波が先、速い高周波が後に観測されるはずで、現象を説明できない。衛星軌道上７分から１０分にわたって朝夕方向に広い範囲で観測されたことを考えると、異なる磁力線上を異なる周波数の波が伝搬している構造中を衛星が通過したと考えざるを得ない。

固有磁場によって保護されていない月面上空で観測されたこと、およびこの時の太陽風フラックスが普段より高かったことから、太陽風粒子の衝突によるスパッタリングや二次電子の放出が期待される。これらの粒子が狭い粒子源から様々な角度に放出されたと考えると、粒子速度は粒子源の直上では磁力線に平行に近く、少し離れたところでは斜めの速度になると考えられる。k に対する各周波数を描いた分散関係図上で、共鳴条件を示す直線とホイスラ波の分散曲線とは、V_{para} の小さいときは高周波、大きいときは低周波で交わるので、粒子源から遠いところで高周波、粒子源の直上で低周波が期待される（ここで V_{para} は共鳴粒子速度の磁力線に平行な成分）。共鳴粒子を電子と考えると、1-12Hz の波が粒子から見て電子サイクロトロン波の周波数に見えるためには太陽風速を超えるビーム速度が必要となりエネルギー的に無理がある。反射粒子がイオンでホイスラ波を追い抜く形で共鳴すると考えると、共鳴粒子速度は太陽風速以内で説明することができる。

Decrease of IMF strength on the lunar dayside and above the polar region observed by Kaguya

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Direct interaction between the lunar surface and incident solar wind is one of the crucial phenomena of the planetary plasma sciences. Recent observations by lunar orbiters revealed that strength of the interplanetary magnetic field (IMF) at spacecraft altitude often increases over crustal magnetic fields on the dayside. In addition, variations of the IMF in the lunar wake have been reported in the viewpoint of diamagnetic effect. However, few studies have been performed for the IMF over non-magnetized regions on the dayside. Here we show events where the IMF strength decreases at ˜100 km altitude on the lunar dayside and over the polar region, comparing the upstream solar wind data from ACE with Kaguya data. (Note that we focus on the magnetic field reduction observed above non-magnetized regions (or very weakly magnetized regions)).

In one event when the IMF is roughly anti-parallel to the solar wind flow, the magnetic field reduction is detected in the dayside northern hemisphere. We estimate that the decrease in the magnetic pressure is partly compensated by the thermal pressure of the back-scattered protons. In another event the IMF reduction is continuously detected from the northern polar region to the dayside mid-latitude region. The Kaguya LRS/WFC data show a slight increase in the electron density around the northern pole, which suggests an increase in the positive ion density. The density increase might be attributed to the back-/forward-scattered solar wind protons as well as heavy ions originating from the lunar surface and/or exosphere, while the heavy ions may not contribute to an increase in the thermal pressure because their temperature is very low.

The observed magnetic field reduction is interpreted as diamagnetic effect by the scattered solar wind protons. We also discuss the diamagnetic current system on the lunar dayside that is added to the wake current system.

MMS衛星を用いた地球Bow shockにおけるホイッスラー波の微細構造の解析

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Microscopic structure of whistler wave packets within Earth's bow shock observed by MMS spacecraft

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Nonthermal charged particles are ubiquitously observed in space plasmas. The Fermi acceleration at a shock wave is one of the most important mechanisms for the generation of high-energy particles. In this mechanism, the pitch-angle scattering is essential for the confinement of the particles in the close vicinity of the shock. Charged particles may be scattered by electromagnetic fluctuations via the cyclotron resonance. Ions easily satisfy the resonance condition with low frequency Alfven waves, whereas the scattering of electrons requires higher frequency whistler waves. Since, in general, the power at lower frequencies is much larger than higher frequencies, the acceleration of electrons is much more difficult compared to ions. In fact, electron acceleration events associated with interplanetary shock crossings are very rare (Lario et al.2003, Dresing et al.2016). The condition that regulates the efficiency of electron acceleration at a shock is poorly understood at present. In particular, we do not know how and when the whistler waves are generated to scatter the accelerated electrons.

In this study, we performed an analysis for high-frequency(~100 Hz) electromagnetic waves observed during shock crossings with enhanced energetic electron flux observed by NASA's MMS (Magnetospheric MultiScale) satellites.

The purpose of this research is to estimate propagation characteristics and spatio-temporal scales of whistler wave packets that appear sporadically in the shock transition layer. First, by applying a bandpass filter to the magnetic field measured by the SCM (Search Coil Magnetometer), we confirmed that high-frequency electromagnetic waves appear as wave packets of very short lifetime. We found that most of the wave packets do no show clear correlations between different spacecraft with a separation distance of ~20 km. This strongly suggests that the wave packets have very small spatial scales. By using MVA (Minimum Variance Analysis) and calculating Poynting vector, we determined propagation directions of individual wave packets. In addition, the wavenumber is obtained from the electric-to-magnetic field ratio using Faraday's law. We will compare the result of the analysis applied for a large number of wave packets observed in a shock with the cyclotron resonance condition of electrons.

We will also estimate the spatial scale sizes of whistler wave packets by comparing events with different spacecraft separations. In particular, we discuss the difference of the scale size in parallel and perpendicular to the local magnetic field. For events with clear correlations between multiple spacecraft, we may also check the consistency between the single spacecraft analysis (MVA and Faraday's law) and the actual multi-spacecraft observations.

宇宙空間には、地球磁気圏内における放射線帯のように非熱的な荷電粒子が普遍的に存在している．高エネルギーの荷電粒子が生成される要因の一つとして衝撃波におけるフェルミ加速が挙げられるが、フェルミ加速では粒子のピッチ角散乱が重要なプロセスとなる．衝撃波近傍で荷電粒子が電磁波とサイクロトロン共鳴することによって散乱され、衝撃波近傍に閉じ込められることによってフェルミ加速が起こる．イオンは低周波のアルフベン波と容易に共鳴条件を満たすのに対し、電子がピッチ角散乱を起こすにはより高周波のホイッスラー波との共鳴が必要となる．一般的に、高周波の方が強度は弱いため、イオンより電子の方が加速はされにくいと考えられている．実際に、衝撃波における電子加速の観測例はイオンに比べて少ないことが知られている (Lario et al.2003, Dresing et al.2016). また電子加速の効率が良いイベントとそれ以外のイベントの違いも明らかになっていない．特に、電子加速に必要なホイッスラー波の生成メカニズムや、生成のために必要な条件など、未解明の点が数多く残されている．

本研究では NASA の MMS(Magnetospheric MultiScale) 衛星によって観測された衝撃波のうち、電子加速が見られたイベントについて、高周波 (〜100 Hz) の電磁的波動について解析した結果を報告する．

本研究は、衝撃波遷移層で散発的に観測されるホイッスラー波の伝播特性および波束の時空間スケールの推定を目的とする．最初に、バンドパスフィルタをかけることによって、短い時間スケールで散発的に現れるホイッスラー波と思われる波束の存在を確認した．また衛星間距離が 20 km 程度の時に複数衛星で観測される波に対応が得られないイベントが多いことから、波束の空間構造が小さいことが示唆される．各波束について MVA(Minimum Variance Analysis) によって波の伝播方向を決定した．しかしこの伝播方向には 180 度の不定性があるため、電場と磁場を用いたポインティングベクトルを求めることにより伝播方向を一意に決定した．また、ファラデーの法則を用いて電場と磁場の比から位相速度を求め、これより波数の絶対値を求めた．これらの解析を各波束について独立に行うことによって、統計的にホイッスラー波と電子のサイクロトロン共鳴条件の関係を議論する．

さらに、MMS 衛星が 4 機からなる編隊衛星であることを用い、衛星間距離の異なる期間のイベントの比較から、ホイッスラー波の波束の空間スケールについてより詳細な推定を試みる．特に磁場に対して平行および垂直成分の波束の空間スケールの違いや、複数衛星で同一の波束が観測された例について MVA およびファラデーの法則から決定した伝播特性との整合性を議論する．

高温イオンを含む無衝突垂直衝撃波の２次元構造

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Two dimensional structure of a collisionless perpendicular shock mediated by hot ions

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It is common in space that a plasma contains hot ions. Velocity distribution function of solar wind protons often show non-thermal tail. Diffuse ions are commonly observed in the terrestrial foreshock.Pickup ions cannot be neglected in the boundary region of heliosphere. In collisionless shocks these hot ions are easily energized and sometimes have great impact on the shock structure. In this study we focus on the impact of the hot ions on the microstructure of a collisionless shock.

Two dimensional microstructure of a collisionless perpendicular shock mediated by hot ions is investigated by using full particle-in-cell simulation. The shock parameters are as follows. Alfven Mach number is ˜6, electron and background ion beta are 0.25 and 0.167, hot ion beta is 20.3, respectively. The relative density of the hot ions is 0.25. The hot ions significantly affect the microstructure of the shock. The shock is relatively stable in comparison with the case without the hot ions. A large scale extended foot is formed due to the reflected hot ions. A variety of waves are generated in the transition region. The largest wavelength among the generated waves in the system is smaller than that in the case without the hot ions. Details of the analysis will be reported.

電波掩蔽による太陽風加速域における準周期変動の観測

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Observation of quasi-periodic fluctuations in the solar wind acceleration region by radio occultation

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For solar wind generation, the pressure gradient caused by the high temperature of the corona reaching 1 million K is important. Coronal heating is one of the unresolved problems of space plasma physics. Though various heating mechanisms such as wave heating and nano-flares have been proposed, confirmation by observational data is insufficient. In recent years, information on the physical process in the lower corona is being obtained by optical remote sensing by solar observation satellites. On the other hand, for the solar wind to be accelerated up to several hundred km/s as observed, the plasma needs to be continuously heated to somewhat far distances from several to ten times the solar radius. This region is too dark to investigate by optical observation, and the temperature is too high for in-situ measurements, and thus the observational data is limited. Radio obscuration observation is one of the limited means that can approach this region.

Observations were carried out using radio waves transmitted from the spacecraft and received at the ground station during the superior conjunction period from 30 May 2016 to 15 June 2016 and the period from 29 December 2017 to 20 January 2018. Solar offset distances of about 2 to 10 solar radii were probed intermittently 11 times in the former period and 10 times in the latter period. Though right-circularly polarized waves are basically transmitted from the spacecraft, left-circularly polarized waves are also transmitted with a much weaker amplitude. By utilizing this fact, by recording both polarized waves at the ground station, it is possible to measure the rotation of the plane of linear polarization (Faraday rotation) due to magnetic field fluctuations caused by Alfven waves. We have already performed similar radio obscuration observations in 2011, but at that time only right-circularly polarized waves were measured, and the radial variations of the plasma density fluctuation due to compressional waves and the solar wind velocity were studied (Miyamoto et al. 2014; Imamura et al. 2014). In the new observation, we also aim to capture magnetic field fluctuations, thereby studying the propagation of Alfven waves from the solar surface and their dissipation and thermalization, which lead to heating of the plasma in the solar wind acceleration region. In this presentation, we report initial analysis of quasi-periodic fluctuations seen in the time series.

太陽風の生成には 100 万度に達する高温のコロナがもたらす圧力勾配が重要である。コロナ加熱は宇宙プラズマ物理の未解決問題の一つであり、波動加熱やナノフレアなど様々な加熱機構が提案されているが、観測データによる検証が不十分である。近年、太陽観測衛星などによる光学リモートセンシングによってコロナ下部の物理過程の情報が得られつつある。しかし一方で、観測されているような数 100 km/s もの速度まで太陽風が加速されるためには、コロナ下部の加熱に加え、太陽半径の数倍から 10 倍程度というやや離れたところまで持続的にプラズマが加熱されて高温が保たれる必要がある。この領域は光学観測で調べるには暗く、探査機が近づいて観測するには温度が高すぎるため、観測データが乏しい。ここにアプローチできる限られた手段のひとつとして電波掩蔽観測がある。

我々は 2016 年 5 月 30 日から 6 月 15 日、および 2017 年 12 月 29 日から 2018 年 1 月 20 日にかけて、金星探査機「あかつき」が地球から見て太陽のほぼ反対側を通過する機会をとらえて、探査機と地上局を結ぶ電波を用いて掩蔽観測を実施した。前者の期間には 11 回、後者の期間には 10 回にわたって、太陽中心からおよそ 2〜10 太陽半径の範囲を断続的に観測した。探査機からは本来は右円偏波だけが送信されるが、弱いながら左円偏波も送信される。このことを利用して、地上局で両偏波を記録することにより、Alfven 波などに伴う磁場変動による偏波面の回転（ファラデー回転）を計測することができる。我々は 2011 年 6 月にも「あかつき」を用いてコロナの電波掩蔽観測を実施したが、このときは右円偏波のみを計測し、ここからプラズマ密度の変動を導出して圧縮波（音波）の動径分布と太陽風速度の情報を得た（Miyamoto et al. 2014; Imamura et al. 2014）。今回はこれに加えて磁場変動を捉えることにより、太陽表面から Alfven 波が伝播して減衰・熱化する過程を太陽風加速域全体でとらえることを目指している。本発表では観測データに見られる準周期変動の初期解析結果を報告する。

太陽風電流シートとVLISM乱流の相関

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Relation of solar wind current sheet and VLISM turbulence

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The heliosphere is a region in the interstellar space occupied by the solar wind plasma. In its boundary region, two important discontinuities (terminal shock and heliopause) are formed. The supersonic solar wind is decelerated to subsonic speed at the terminal shock, then further decelerated downstream, and finally dammed up by the interstellar medium at the heliopause. The structures of the magnetic field and density in the boundary region are unclear. Voyager 1 has explored the region for the first time and is now sailing VLISM (Very Local InterStellar Medium) beyond the heliopause. In the VLISM the Voyager 1 observes compressible magnetic turbulence. Although its origin is unknown, a number of models are proposed. Here, we study the possibility that the interaction between the solar wind current sheet and the termination shock, or the heliopause, generates magnetic fluctuations and they propagate to the VLISM beyond the heliopause.

Using a one-dimensional PIC simulation, which is the first principle simulation of a collisionless plasma, we reproduce the interaction between the two discontinuities (termination shock and heliopause) and current sheets. As an initial setup, we divide the simulation system into two halves and fill each region with the solar wind plasma and the interstellar plasma. The simulation is performed in the solar wind rest frame so that the interstellar plasma has a constant flow speed. By injecting the interstellar plasma continuously from the left boundary, two shocks (terminal shock and bow shock) and a tangential discontinuity (heliopause) are self-consistently formed. Ratios of parameters between the interstellar plasma to the solar wind plasma are as follows. Plasma density = 9, temperature = 4 (Te = Ti), magnetic field strength = 6, and the inflow velocity of the interstellar plasma was 4.7 times the solar wind Alfvén velocity, respectively. It is confirmed that the passage of the current sheets results in the generation of magnetic fluctuations and those fluctuations propagate to the VLISM beyond the heliopause. In the poster, details of the characteristics of the magnetic fluctuations and the modification of the current sheets etc. will be reported.

太陽を起源とする太陽風プラズマは星間空間の一部を占め、その勢力圏は太陽圏と呼ばれる。太陽圏の境界領域には、2つの重要な不連続面（終端衝撃波と太陽圏界面）が形成されている。超音速の太陽風は、終端衝撃波で亜音速に遷移し、その後さらに減速して最終的に太陽圏界面で星間媒質によりせき止められる。境界領域の磁場や密度構造には未解明の点が多いが、同領域を初めて直接探査したボイジャー1号は、太陽圏界面を超えて現在星間空間のVLISM（VeryLocal InterStellar Medium）を航行中である。ボイジャー1号は、VLISMで圧縮性の磁気乱流を観測しているが、その起源はわかっていない。これまでに提案されているモデルには、VLISMで局所的に励起されたとするもの、ボイジャー以遠の星間空間で励起されて伝搬してきたとするもの、太陽圏内で励起されたものが界面を超えて伝搬するものなどがある.

本研究では、太陽風電流シートが太陽圏境界の不連続面を通過する際に生じる磁場揺らぎが、太陽圏界面を超えてVLISMを伝搬し、VLISM乱流を生成する可能性について探る。

無衝突プラズマの第一原理計算であるPICシミュレーションを用いて、太陽風とともに運ばれる電流シートが終端衝撃波および太陽圏界面を通過する過程で磁場揺らぎを生み、これが伝搬する様子を再現する。初期に1次元空間を2つの領域に分け、右側を太陽風プラズマ、左側を星間プラズマで満たす。計算は太陽風静止系で行い、星間プラズマを一定速度で右側に流入させることで、終端衝撃波、太陽圏界面（およびバウショック）を自己無撞着に生成する。太陽風プラズマに対する星間プラズマの各パラメータの相対的な値は、密度＝9、温度＝4、磁場強度＝6とし、星間プラズマの流入速度を太陽風アルフベン速度の4.7倍とした。電流シートの不連続面通過によって磁場揺らぎが生じること、またそれらが太陽圏界面を超えてVLISMに伝搬することを確認した。発表では、相互作用による電流シートの変性や磁場揺らぎの特性の詳細について報告する。