

## 最高エネルギー太陽放射線予報システム WASAVIES WASAVIES: Warning System of AViation Exposure to SEP

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The prediction of solar energetic particles (SEP) is important to mitigate the space weather hazard toward increasing solar activities, and is also an ultimate problem for physics-based modelers because of the hybrid nature of MHD fluid and particles. We are developing a two-step forecast system called Warning System of AViation Exposure to SEP (WASAVIES) as follows: 1) Detect ground level enhancement (GLE) onset by multiple ground-based neutron monitors [Kuwabara et al., Space Weather, 2006] and obtain the GLE, solar wind, and flare parameters to publish the preliminary forecast within one hour after X-ray flare detection. At this stage we have only a small number of necessary parameters, and available forecast may be limited about the anisotropic GLE dose map and the maximum level of SEP fluence during coming 7 days. 2) Within 6 hours after the flare onset, automatically obtain the CME parameters such as speed and direction parameter to predict the CME driven SEP profiles during the 7 days in the energy range from 10 MeV to 10 GeV. The modified MHD Cube model [Kataoka et al., J. Geophys. Res., 2009] calculates the time-varying CME shock strength and the magnetic field connectivity to Earth for a particle model to estimate the SEP spectra, and also estimate the weekly profiles of solar wind parameters which are necessary inputs for T05 storm model to estimate the cutoff latitudes. Using the SEP energy spectra and cutoff latitudes, the aviation dose map are evaluated by modified PARMA model [Sato et al., Radiat. Res., 2008]. The real-time data of SEP, solar wind, and geomagnetic activities are also utilized properly. In the presentation, we report the current situation of the development of WASAVIES.

## 高エネルギー太陽放射線が引き起こす空気シャワーシミュレーションの精度検証 Verification of the Air Shower Simulation Induced by Solar Energetic Particles

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大気に入射した高エネルギー太陽放射線 (SEP) は大気圏内で空気シャワーを引き起こし, 中性子など様々な2次粒子を発生させる。航空機乗務員のSEP被ばくは, 主にそれら2次粒子によりもたらされるため, その被ばく線量を的確に評価するためには, 精度の高い空気シャワーシミュレーションが不可欠となる。そこで我々は, 原子力分野で数多くの実績を持つ汎用モンテカルロ放射線挙動解析コードPHITS[1]を用いて大気圏内に単色の陽子が入射したときの挙動を解析し, 各高度における放射線フラックスのデータベースを構築した。そして, そのデータベースとPAMELAで測定した2006年12月13日の陽子フラックスを組み合わせ, GLE時のThule中性子モニタの計数率を計算した。その結果, 計算値と実測値はよく一致することが分かり, 本研究による空気シャワーシミュレーションの妥当性が証明された。発表では, この精度検証結果について紹介するとともに, SEP被ばくが航空機乗務員に与える影響について考察する。

[1] <http://phits.jaea.go.jp/>

キーワード: 高エネルギー太陽放射線, 被ばく線量, 空気シャワーシミュレーション, 太陽フレア, GLE

Keywords: SEP, radiation dose, airshower simulation, solar flare, GLE

## Ground Level Event の統計解析について Statistics of Ground Level Events

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500MeV を超えるような太陽高エネルギー粒子は、地上の宇宙線モニターでも観測される場合がある。このような現象を Ground Level Event (GLE) と呼んでいる。GLE の発生は、太陽活動の極大付近で多くなるが、極小付近で発生することもある。地上での宇宙線の観測は、1940 年代頃に始められ、これまでに 70 件程度の GLE が観測されている。

太陽面での発生経度分布、太陽フレアや CME との関係、マイクロ波バーストとの関係などこれまで多くの GLE に関する統計的な解析が行われている。本発表では、これまでの研究成果のレビューとこれまでに観測された GLE に関する解析について報告する。

キーワード: GLE, 太陽フレア, マイクロ波バースト, 宇宙天気

Keywords: GLE, solar flare, solar microwave burst, space weather

## WASAVIES のためのフレア CME イベント認知システムの性能評価 Performance Evaluation of Automated Flare-CME Event Recognition System for WASAVIES

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Solar Energetic Particles (SEPs) are accelerated by interplanetary shocks driven by coronal mass ejections (CMEs). The intensity of the SEP events is closely related to the CME speed, width, and source location. SEPs pose significant radiation hazard to space systems and aviation, so it is important to predict the SEP events. The Warning System of AViation Exposure to SEPs (WASAVIES) is an initiative to forecast the expected exposure to SEP events at the latitude of commercial aircraft. The aim of this work is to obtain the CME parameters in real-time for better prediction of SEP events. The work involves the identification of CME source regions using soft X-ray flares and CME kinematics using automatic recognition of CMEs.

NOAA Space Weather Prediction Center has issued X-ray flux alert when flare X-ray flux exceeds the M5 level. Twenty four major flare alerts were issued between February 2010 and January 2012. Out of the 24 flares, 18 were associated with the CMEs. Our automated CME recognition system could detect all the CMEs but the obtained CME speeds were significantly lower than the CME speed measured by human eyes. We need to optimize parameters in the CME recognition system to obtain the better results.

Keywords: Space Weather, CMEs, Flares

## 太陽全球磁場観測に基づく全自動宇宙天気モデルの開発 Development of automatic daily MHD simulation system of inner heliosphere

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Interplanetary magnetic field (IMF) plays an essential role for energetic particle transport. Global IMF in the heliosphere is originated from open coronal magnetic field and dragged by solar wind. Coronal mass ejections (CMEs) changes IMF as they propagate in the inner heliosphere in addition to generating energetic particles. Therefore realistic modeling of solar wind and CMEs is an essential part of energetic particle modeling.

We recently have developed 3 dimensional global MHD simulation system of inner heliosphere. The simulation is based on minimal input, daily synoptic map of photospheric magnetic field. As a first step, we calculate coronal magnetic field with potential field source surface model and obtain maps of open magnetic field and expansion factor. Applying empirical models (such as Wang-Sheeley-Arge model), we obtain solar wind synoptic map. Using time series of the solar wind maps as the inner boundary(25 solar radii), we perform the global MHD simulation in 2 AU. MHD parameters at the Earth position are passed to a radiation belt model. These programs are executed everyday on a server in STEL, Nagoya university. We have been developing additional module to inject CMEs containing magnetic flux ropes.

キーワード: 宇宙天気, 太陽風, 磁場, 光球

Keywords: space weather, solar wind, magnetic field, photosphere

## 惑星間ショック到来に関係した低高度 SEP の統計解析 Low-altitude SEP precipitation associated with interplanetary shocks

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Enhancements of solar energetic particle (SEP) associated with interplanetary shocks are investigated using the low-earth orbit POES satellite data. The POES satellites have ion detectors that can measure from 30 keV to 7 MeV. We demonstrate the superposed epoch analysis of MeV ions associated with the interplanetary shocks during solar cycle 23. The enhancements can be seen at the invariant latitudes larger than 60 deg. It is expected that these ions are accelerated by the interplanetary shock.

キーワード: 低高度 SEP, 惑星間空間ショック

Keywords: low-altitude SEP, interplanetary shock

## Development of GLE alarm system and observation of recent SEP events by neutron monitors

### Development of GLE alarm system and observation of recent SEP events by neutron monitors

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We have developed a system that watches for count rate increases recorded in real time by eight neutron monitors, which triggers an alarm if a ground level enhancement (GLE) is detected. In this work, we determine optimal strategies for detecting the GLE at a very early stage, while still keeping the false alarm rate at a very low level. The highest level alarm, which we term an "alert," is generated when a 4% increase is recorded at 3 stations in 3-min averaged data. At this level the false alarm rate obtained by backtesting over the 4.4 years from October 2000 to May 2005 is zero. Ten GLEs occurred in this period, and our system produced GLE alarms for nine events. Alarm times for these nine events are compared with satellite proton data. The GLE alert precedes the earliest alert from GOES (100 MeV or 10 MeV protons) by 10-30 min. An automated e-mail alert system is now under beta testing at <http://www.bartol.udel.edu/~takao/neutronm/glealarm/index.html>. Real-time GLE data may be viewed at <http://neutronm.bartol.udel.edu/spaceweather>. We also report the recent observation of solar energetic particle events in this year.

キーワード: GLE, SEP, Neutron Monitor, Cosmic Ray

Keywords: GLE, SEP, Neutron Monitor, Cosmic Ray

## 太陽風中における高エネルギー粒子伝搬の数値シミュレーション Numerical simulation of energetic particle transport in solar wind

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Solar energetic particles are accelerated at a region of a solar flare and a shock wave in a solar corona and/or a solar wind. Especially, particles can be sometimes accelerated to GeV energy at the flare region and the coronal shock wave. These extremely energetic particles are propagated to the Earth in the solar wind and cause ground level enhancement (GLE). As turbulent magnetic fields exist in the solar wind together with a back ground magnetic field (Parker magnetic field), the energetic particles are transported in the solar wind along the back ground magnetic field suffering pitch-angle scattering by turbulence. The energetic particle transport in the solar wind is often described by a focused transport equation. We have developed a numerical simulation code to solve the focused transport equation to reproduce a particle flux observed near the Earth. In the presentation, we introduce our developing numerical simulation code and give some results of numerical simulations of GeV particle transport in the solar wind.

キーワード: 高エネルギー粒子, 太陽風, 確率微分方程式

Keywords: energetic particle, solar wind, stochastic differential equation



## 衝撃波域での粒子拡散現象

### Particle diffusion process around collisionless shocks

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拡散対流方程式から議論されているように、衝撃波近傍での粒子加速では、上下流域での粒子の運動は、酔歩運動をもとにした拡散現象で解釈がされている。拡散係数を決める波動粒子相互作用は、線形理論、もしくは準線形理論を基にしたピッチ角散乱から計算されている。しかし、実際に宇宙空間で観測されている電磁波動強度は、背景磁場強度程度の振幅をもち、非線形波動粒子相互作用が考えられる。つまり、波動による粒子の位相補足と開放が繰り返され、拡散過程が古典的拡散とは異なる事が考えられる。本講演では、最近の人工衛星による観測結果とシミュレーション結果から示唆される粒子の運動について紹介する。例えば、イオン粒子の運動論を取り入れたシミュレーションでは、個々の粒子軌跡を記録している。そこで得られた軌道は、酔歩のような運動ではなく、Levy Flight と呼ばれる「移動」と「滞在」で表現されるものであり、より遠くまで粒子が移動していることが確認された。また、エネルギースペクトルは、よりハードとなっている。

キーワード: 衝撃波, 粒子拡散

Keywords: shock wave, particle diffusion

## 金星探査機あかつきに対する太陽高エネルギー粒子被曝量の評価 Evaluation of solar energetic particles exposure on the Venus orbiter Akatsuki

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Space weather researches have become more and more important, according to the expansion of the "humanosphere" to the space. On the other hand, current space weather researches are mainly for circumterrestrial space, not for the deep space probes that are located far from the earth. We aim to forecast and evaluate the radiation hazard to such space probes far from the earth by using the data taken by the Solar Terrestrial Relations Observatory (STEREO). STEREO provides the images of the part of the Sun that is invisible from the Earth, but only EUV images and coronagraph images are available.

First, we examine the possibility of the evaluation of the radiation hazard by using EUV and coronagraph images. It is known that solar energetic particles (SEPs) flux is well correlated with the speed of coronal mass ejection (CME) measured by a coronagraph. We focused on two successive flare/CME events occurred on June 4th, 2011. It occurred in an active region that located on the invisible side of the Sun, and near the disk center as seen from Akatsuki (PLANET-C), the Venus Climate Orbiter that was orbiting the Sun at around 0.7AU. On June 5th, an abrupt decrease in the electric power of Akatsuki was observed, which may be attributed to the effect of SEPs associated with the flare/CME events.

We measured the velocity of the two CMEs using the coronagraphic images from STEREO and found that the second CME was much faster (about 2200 km/s) than the first one (about 1000 km/s). Considering the time difference between the two events, it is likely that the second CME caught up the first one before they arrived at 0.7AU. The estimated arrival time is consistent with the timing of the power decrease of Akatsuki. According to a statistical study of CMEs and SEPs performed by Gopalswamy et al. (2004) SEP flux tends to become large if a preceding CME have been launched within 24 hours ahead of the onset time of the primary CME. Using the empirical relationship between the SEP flux and the CME velocity derived by Gopalswamy et al. (2004), we estimate the SEP flux of  $10^2$ - $10^4$  cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>. We are also analyzing other large events that may potentially affected Akatsuki such as that occurred on January 23 2012.

キーワード: 太陽フレア, CME, SEP, 宇宙天気

Keywords: Solar flare, CME, SEP, Space weather

## Influence of solar energetic particles on unmagnetized celestial bodies Influence of solar energetic particles on unmagnetized celestial bodies

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High energy particles associated with solar flares (solar energetic particle; SEP) significantly influence the atmosphere and the surface of non-magnetized planetary bodies. In this presentation, we will show recent observations conducted in the vicinity of Mars and Venus demonstrating the importance of the SEPs on those bodies. In addition, we will also discuss the expected SEP effects on non-atmospheric bodies, such as the Moon.

Without the shielding by the magnetosphere, unmagnetized bodies are directly exposed to the SEPs. As a result, the response of the planetary bodies to the SEPs would be expected to be immediate and harsh. During the famous Halloween event in 2003, Mars Global Surveyor observed a compression of the Martian plasma environment and resulting enhancement of the magnetic field in the ionosphere caused by SEPs and CMEs (Crider et al., 2005). Signatures of the entry of the solar wind protons into the low altitude in the dayside and the enhancement of cyclotron waves associated with proton and oxygen ions in the nightside were found (Espley et al., 2005). These imply the increase of the atmosphere erosion, mainly oxygen ions, into space. During other moderate SEP events, Morgan et al. [2006] reported evidence for an additional ionospheric layer using active radar experience on board Mars Express, indicating the extrordinaly ionization of the atmosphere by the SEPs.

On December 5, 2006, one of the largest flares erupted from the east limb of the Sun. This was a geo-effective flare, but it influenced a wide area of the inner solar system including Mars (about 160° west of the Earth) and Venus (about 160° east of the Earth). Plasma sensor packages, ASPERA-3 and -4 on board Mars Express and Venus Express respectively, detected signatures of the SEPs as a high background count rate of the sensors. The high background condition lasted for a few days, and a higher (about 10 times more than usual) flux of outflowing oxygen ions was detected directly in the plasmatail for the first time. The increasing outflow of oxygen ions occurred before the arrival of the associated CMEs (Futaana et al., 2008). These observations indicate that the SEPs do influence the upper atmosphere to increase the escape of oxygen ions eventually, and thus, the high energy particle environment is one of the significant keys to investigate the atmospheric evolution of the solar system bodies in geological time scales.

キーワード: Solar Energetic Particle, Mars, Venus, Erosion, Moon

Keywords: Solar Energetic Particle, Mars, Venus, Erosion, Moon

## 航空機運航中における宇宙線被ばく Cosmic-ray exposure during aircraft operation

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Effects of exposure to cosmic-ray during aircraft operation, are divided into the exposure of the crew and operational impact.

International Commission on Radiological Protection(ICRP) issued a recommendation to include occupational exposure of aircrew with a jet operated exposure from natural radiation source in 1990.

Radiation Council consists of the Ministry of Education, Culture, Sports, Science and Technology, the Ministry of Health, Labour and Welfare, the Ministry of Land, Infrastructure, Transport and Tourism established "Guidelines for management of aircrew exposure to cosmic radiation" in 2006.

In response to this, airlines manage doses on each aircrew using Japanese Internet System for Calculation of Aviation Route Doses(JISCARD) developed by National Institute of Radiological Sciences(NIRS).

Examples of operational impacts are, communication difficulty on short wave due to Dellinger Phenomenon during international flight, and rewrite the data in memory known as soft error on electronic equipment onboard aircrafts.

Use of Space Weather forecast for major solar flare, how to provide the information to aircrew and how to make decisions are urgent consideration.

## 太陽フレア現象における粒子加速と高エネルギー粒子の地球への伝搬 (II) Particle acceleration in solar flares and propagation of high energy particles to the Earth (II)

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第 24 太陽活動期に入り、太陽はとても活動的になっている。太陽表面には数多くの黒点が現れ、「太陽フレア」と呼ばれる爆発現象も、大規模なものまで数多く発生している。この太陽フレアや、CME などのフレアに伴って発生したと考えられる現象により、多くの粒子が高エネルギーまで加速されていることが観測から分かっている。大規模なイベントにおいては、これらの加速粒子が大量に地球まで到達することもある。これによって、地球磁場の擾乱や地上における宇宙線量の増加 (Ground Level Enhancement: GLE) が引き起こされ、我々人間の生活にまで影響することがある。

高エネルギー粒子発生の起源となっている太陽フレア現象は、近年、電波から 線までの多波長観測が衛星などを用いて行われている。特に加速粒子の情報としては、硬 X 線から加速電子の、そして核ガンマ線から加速イオンの情報が得られる。また、地球まで到達した高エネルギー粒子は地上に設置されている中性子モニターなどで観測されている。これらの観測データを比較研究することによって、どのくらいの規模のフレアのとときにどのくらいの高エネルギー粒子が地球までやってくるか、予測することができる可能性がある。

このような高エネルギー粒子の生成機構としては主に、(1) フレア単独による加速、(2) フレアである程度加速し、その後惑星間空間を伝播する CME の衝撃波面で加速するという、二つのモデルが考えられているが、詳細は明らかになっていない。いずれにせよ、地球まで到達する太陽高エネルギー粒子量の予報のためには、太陽面での高エネルギー粒子分布の定量的な理解が重要である。

本発表では、宇宙線被曝予報の確立にむけて、太陽面における高エネルギー粒子の分布についてと、これらが地球まで到達した時における高エネルギー粒子 (太陽中性子) のエネルギースペクトルの予測例について紹介する。また、2012 年 1 月 23 日に発生した M8.7 クラスの太陽フレアに伴った大規模 SEP イベントについて、太陽観測データから原因の検証を行う。

キーワード: 太陽フレア, 粒子加速

Keywords: solar flare, particle acceleration

## AMR と確率微分方程式法を用いた衝撃波加速のシミュレーション Simulations of Diffusive Shock Acceleration with AMR Scheme and SDE Method

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コロナ質量放出 (CME) 起源の惑星間空間衝撃波により加速された高エネルギー粒子フラックスの増加現象の、シミュレーションによるモデリングを試みている。粒子フラックスは通常 CME 発生後から増加し、衝撃波通過と同時にピークとなるため、衝撃波が磁気圏じょう乱のトリガーとなることから、粒子フラックスのふるまいは宇宙天気予報に結びつく直接的な前兆現象と言える。粒子フラックスは、衝撃波により加速されている粒子と、加速領域から逃れて伝搬してくる粒子の双方から形成されていると考えられるが、ここでは衝撃波加速を扱う。

粒子の加速を決めるのは、衝撃波の圧縮比、拡散係数、被加速粒子のエネルギー分布、ショック角が重要となるが、これらは時間・空間的に変化している。これまで衝撃波の時間・空間の変化を取り込むことを目的にして、適合格子法 (Adaptive Mesh Refinement) を用い、衝撃波の伝搬過程の 3 次元数値シミュレーションを行って、その結果を確率微分方程式法を入力することにより、加速過程と衝撃波伝搬過程を結合させた。結果としては、圧縮率は衝撃波形成から地球軌道まで数倍程度の変化で、粒子の加速には大きな影響を及ぼさないことを示した。

今回我々は、拡散係数に着目する。ここでは拡散係数を粒子のエネルギーと衝撃波面からの距離の関数として扱い、衝撃波加速のモデリングを行う。それまでの拡散係数一定とした場合と比較し、拡散係数の影響について考察する。

キーワード: 衝撃波加速, 高エネルギー粒子, 適合格子, 確率微分方程式

Keywords: shock acceleration, high energy particle, Adapted Mesh Refinement, Stochastic Differential Equation

## Effects of 2012 solar energetic particle events measured near multiple planets in the inner solar system

## Effects of 2012 solar energetic particle events measured near multiple planets in the inner solar system

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The solar energetic particles (SEPs) observed at the Earth exceed 6000 PFU at  $>10$  MeV protons in January 23 and March 7 associated with M8 and X5 flares and associated coronal mass ejections, respectively. The SEP flux is the largest in the last 8 years. Mercury, Venus, and Mars are on the same side of the Sun, making particularly the March event very unique to understand the radiation effect at multiple planets and to understand the SEP distribution itself via the comparison of the observations and models at different positions. Indeed, there are operating spacecrafts, not only near the Earth, but near Mercury, Venus, and Mars in addition to Stereo spacecrafts which provide information on the environment of interplanetary space. In this presentation, we overview the 2012 solar flare events and report the observations by spacecrafts (Mars Express, Venus Express and others) at multiple planets.

キーワード: Solar Flare, Energetic particle event, Inner solar system

Keywords: Solar Flare, Energetic particle event, Inner solar system