Energetic Particle Chain -Effects on the Middle/Lower Atmosphere from Energetic Particle Precipitations-

Research aims and background

Energetic particle precipitation (EPP) due to solar activity, such as solar proton events and magnetic storms, occurs in polar regions. EPP particles create odd nitrogen (NO_x) and odd hydrogen (HO_x), which can affect the neutral chemistry of the middle atmosphere and the ozone (O_3) concentration. This is related to a problem which is one of the key questions in the SCOSTEP/PRESTO program: "What is the chemical and dynamical response of the middle atmosphere to solar and magnetospheric forcing?" To answer this, it is important to understand the behavior of energetic particles in the magnetosphere, ionosphere, and upper/middle atmosphere as a causal chain reaction system (Fig.1), based on observations in each region and comprehensive simulations.

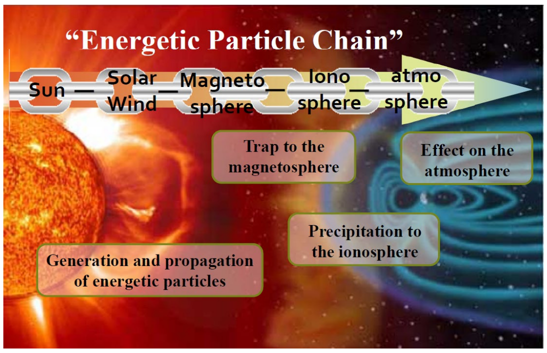


Fig.1: Image of a causal chain reaction system.

In this context, we started a new research project called the energetic particle chain. This project plans to conduct multi-point and long-term observations of the trapped particles in the magnetosphere with the Arase satellite, EEP-induced ionization in the ionosphere with the EISCAT_3D radar and riometers, and the variation of atmospheric molecules from the lower thermosphere to the upper stratosphere with millimeter-wave spectroradiometers in the polar region of the Northern Hemisphere (Fig.2). These measurement data will be used as inputs and constraints in modeling, such as integrated simulation codes of EPP, ion chemistry in the atmosphere, and global dynamics/temperature fields. Measurements are also useful for assessing the validity of the model output.

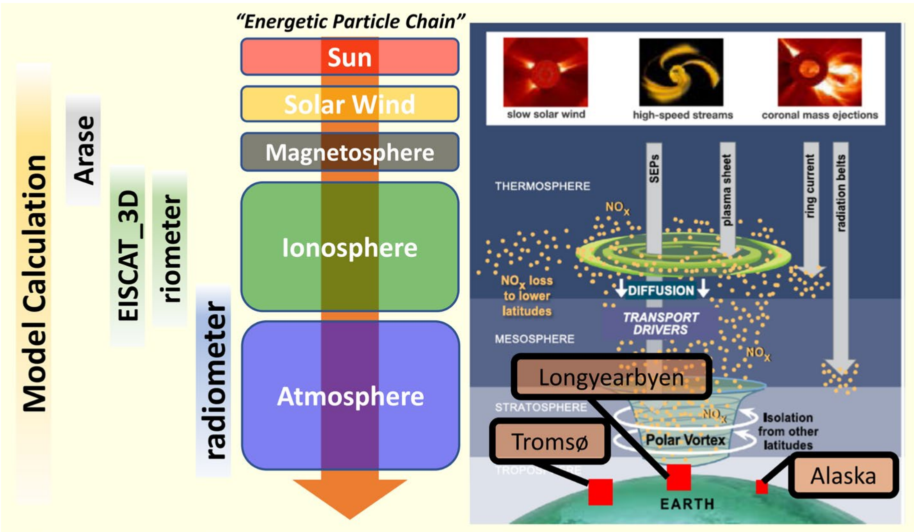


Fig.2: (left side) Observational region with each instrument and data fusion with simulation. (right side; modified from Marshall et al., 2020) Relationship between the energetic particle precipitations and new observation sites.

Results in FY2021

1. We developed a method to derive the downward energy flux and characteristic energy of aurora electrons from observations at two different wavelengths and applied the method to a pulsating aurora using camera data from Tromsø.
2. We studied pulsating auroral morphology and its precipitation electron energy flux by analyzing measurements from a high-speed sampling camera and riometers in Finland. Energy spectrum hardening and softening were detected at pulsating periods shorter and longer than 40 s, respectively, in association with pulsating auroral patch formation. Hardening was identified on the equatorward side of the pulsating aurora.
3. We developed a code that calculates the pitch angle scattering via both quasi-linear processes and non-linear processes. We also developed a code to calculate the height profile of the auroral emission at each wavelength and CNA absorption using the precipitating electrons.

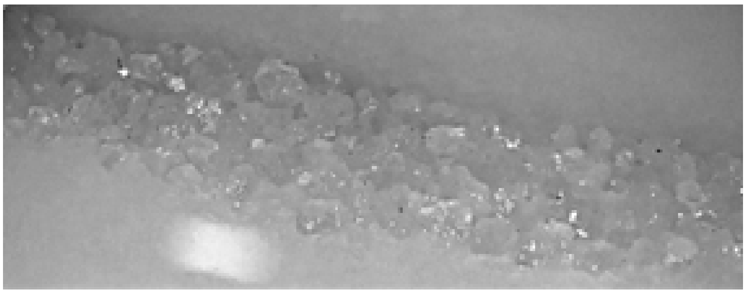
Direct Search for Dark Matter with Paleo-Detectors

Although dark matter constitutes about a quarter of the universe, it cannot be observed optically and its true nature remains a mystery. Several studies have been conducted to determine what this substance is. For example, the XENONnT project uses tons of liquid xenon in a direct search; in a direct search, the detection sensitivity is limited by the product of the mass of the detector and the experimental time. The time cannot be stretched indefinitely in experiments by humans, and methods using liquid xenon reach the limits of scale. Therefore, the method of using minerals as detectors and the 'paleo-detector' method are attracting attention. Minerals interact with dark matter on a geological scale of time; therefore, even small quantities of minerals have the potential to search for dark matter with sensitivity exceeding that of large-scale experiments. Our project combines petrology, geochronology, particle astrophysics, X-ray spectroscopy, electron microscopy, and analytical chemistry to directly search for dark matter and other unknown elementary particles using a paleo-detector. The method assumes that dark matter is a WIMP and reads the tracks produced by the interaction of dark matter with atoms in minerals, from which the scattering cross sections of dark matter and atoms are deduced.

Direct dark matter searches using paleo-detectors have a long history, and Snowden-Ifft et al. (1995) [1] observed mica etched with hydrofluoric acid using atomic force microscopy (AFM). However, no dark matter was detected. Drukier et al. [2] identified rock salt, epsomite, olivine, and nickelbischofite as candidates, with low uranium concentrations being a prerequisite for paleo-detectors. Edwards et al. [3] considered nchwaningite and sinjarite as candidates. Baum et al. [4] also submitted a letter of interest (LOI) on the direct search for dark matter by paleo-detectors during the Snowmass Process. Electron microscopy, ion-beam microscopy using helium, AFM, and synchrotron radiation have been proposed as possible read-out methods.

In our project, we are working toward proof of principle with the following considerations regarding the selection of minerals and the methods of reading the tracks. For the mineral samples, we decided to use olivine collected from the seabed and olivine from xenoliths in Quaternary basalts, considering the low noise due to cosmic rays and the possibility of preparing sufficient samples. For the readings of the tracks, we considered the optical readout method of the etched samples. First, olivine was measured by inductively coupled plasma mass spectrometry (ICP-MS) using a solution method to assess whether the uranium concentration was very low. The results showed that olivine was present in low concentrations, as assumed in theoretical studies [2][3][5]. A preliminary experiment using muscovite also revealed that tracks formed under conditions where nuclear inhibition was dominant could be easily identified. As white mica can be dated by the K-Ar method, its effectiveness as a paleo-detector will be investigated in the future.

In the future, the project will continue by trying out white mica, which was also used in the direct search for magnetic monopoles [6], and by considering the possibility of searching for dark matter and various unknown elementary particles.



Olivine in lherzolite from Mariana trench.

[1] Snowden-Ifft, D.P., E.S. Freeman, and P.B. Price, *Phys. Rev. Lett*., 74, 4133, 1995
[2] Drukier, A. K., S. Baum, K. Freese, M. Górski, amd P. Stengel, *Phys. Rev. D*, 99, 043014, 2019
[3] Edwards, T. D. P., B. J. Kavanagh, C. Weniger, S. Baum, A. K. Drukier, K. Freese, M. Górski, and P. Stengel, *Phys. Rev. D*, 99, 043541, 2019
[4] Baum, S., E. Brown, T. D. P. Edwards, K. Freese, J. R. Jordan, C. Levy, K. McMichael, K. Odgers, M. Schaller, J. Spitz, and P. Stengel, *Snowmass 2021 LoI*, 2021
[5] Kato, T., Y. Kozaka, Y. Asahara, Y. Kouketsu, and K. Michibayashi, 2021, JAMS2021.
[6] Ghosh, D., and S. Chatterjea, *Europhys. Lett*., 12, 25, 1990

Data Rescues of the Analog Observational Records for the Past Solar-Terrestrial Environment

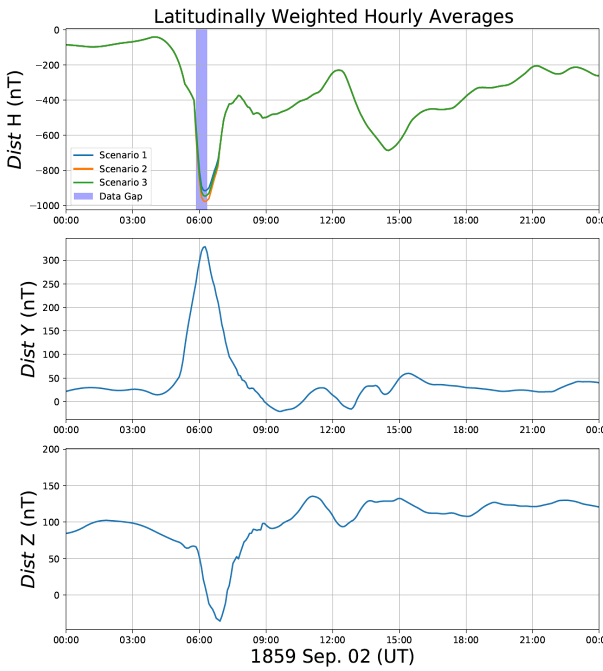
Variable solar-terrestrial environments are closely related to the humanosphere of modern civilizations. Solar eruptions and the resultant space weather disturbances often significantly impact modern human infrastructure. However, modern datasets frequently have limitations in their chronological coverage, especially when understanding the variability of such solar-terrestrial environments. It is only since the International Geophysical Year (1957–1958) that multiple observational record series have been systematically archived under international collaborations. In this context, analog records and historical documents have often benefitted studies on extreme space weather events. Therefore, our team investigated historical observations to survey, collect, and digitize their analog records. In this fiscal year, our team obtained significant results for the analog records for visual aurorae, sunspots, and geomagnetic measurements based on analog collections and yearbooks.

Our team collected and analyzed Japanese visual auroral reports around the International Geophysical Year (IGY:1957–1958), for which only the air overview and fragmental episodes are well known to the scientific community. We have published our results as Hayakawa et al. (2022, *Geosci. Data J.*, DOI:10.1002/gdj3.140) based on our archival investigations. On this basis, we confirmed the equatorward extension of the auroral oval in September 1957 and February 1958, at least down to over the Tsugaru Strait and Aomori, respectively. These results have been widely broadcast in Japanese newspapers such as Hokkaido Shinbun, Asahi Shinbun, and Chunichi Shinbun.

Furthermore, our team has also significantly developed our research on the Carrington storm of September 1859 (Hayakawa et al., 2022, *Astrophysical. J.*, 928, 32, DOI: 10.3847/1538-4357/ac2601), which is considered to be one of the greatest space weather events in the space weather community. Our team located copies of yearbooks for Bombay geomagnetic measurements in British India in several libraries, such as the British Library. Our team obtained these copies to find parallel measurement results in an hourly cadence and variable shorter cadence in 5–15 minutes, detect their apparent discrepancies around the Carrington peak in the geomagnetic horizontal component, newly derived variabilities of the eastward and vertical components, and reconstructed their diurnal variations and disturbance variations. These results directly benefit scientific discussions of their magnitude and temporal variations.

Our team has progressed in our analyses of sunspot records, especially based on Hitoshi Takuma's sunspot drawings in 1972–2013 at the Kawaguchi Science Museum following an international collaboration with the Kawaguchi Science Museum, the Royal Observatory of Belgium, and the National Astronomical Observatory of Japan. On this basis, we have revealed that Takuma's data are richer than previously known to the scientific community and one of the best data stability among the long-term sunspot observers known to the scientific community (Hayakawa et al., 2022, *Geosci. Data J.*, DOI:10.1002/gdj3.158). This result is important not only for the sunspot number recalibration itself but also for the confirmation of the scientific value of the long-term observers' individual sunspot observations in our country.

As such, past analog records allow us to develop several scientific discussions and analyses on the long-term variability and short-term space weather disturbances of solar-terrestrial environments. Our team is going to expand these studies to further archival materials to better understand solar-terrestrial environments for long-term variability and short-term eruptive events.



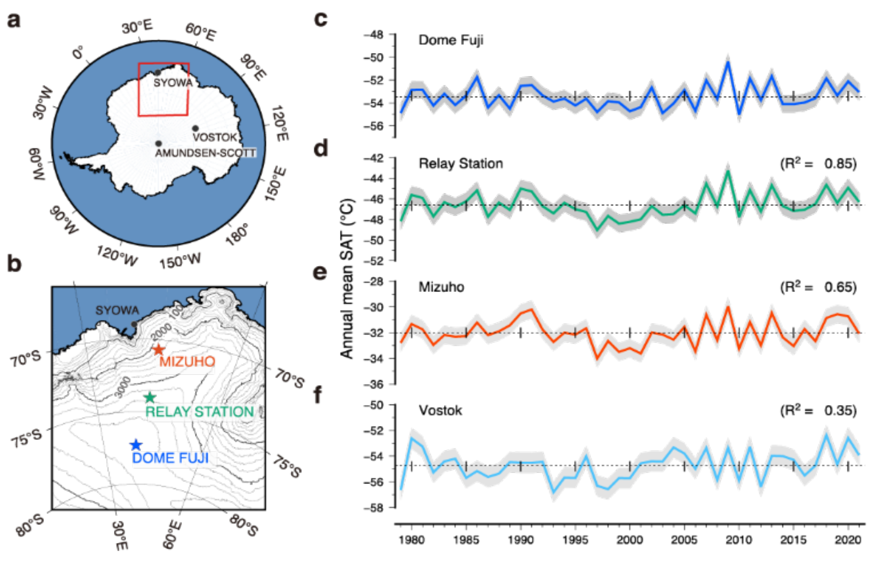
Temporal variations of the three geomagnetic components at Colaba during the Carrington storm (Hayakawa et al., 2022, *ApJ*, 928, 32).

Changes in Surface Temperature at Dome Fuji in East Antarctica from the Mid-Twentieth Century and the Impact of Solar Activity

Cosmogenic isotopes such as ^{10}Be and ^{3}HHO are mainly produced in the stratosphere by the interaction of cosmic rays. After production, these enter the atmospheric circulation in the troposphere and are then deposited on the ice sheet in Antarctica. Thus, the concentrations of cosmogenic isotopes preserved in ice cores from Antarctica can be used as a proxy for past cosmogenic records. However, they not only reflect the production rate in the stratosphere but are also influenced by transport and deposition processes in the troposphere. To translate isotopic records in ice cores into the stratosphere production rate, it is necessary to understand these influences on the variability of the production rate. Here, we aim to explore the temporal variations of the cosmogenic isotopes during the past 70 years by modeling their production and deposition and quantitatively analyzing the extent of the increase/decrease in the production rate in the upper atmosphere recorded in the ice cores in Antarctica. In this project, we will correct the snow samples accumulated after the 1950s in inland Antarctica and present high-resolution measurements of ^{10}Be and ^{3}HHO over the last 70 years. Thereafter, by comparing with the modeled temporal variability of the production rate, we will assess the impact of atmospheric processes.

This year is the first year of this project and we joined a field trip to the Dome Fuji site in East Antarctica as part of the Japanese Antarctic Research Expedition (JARE) and carried out snow sampling at Dome Fuji (77.31°S, 39.70°E, 3810 m als). We collected snow samples with a 3 cm depth resolution from the wall of the snow pit (5.3 m depth) drilled at Dome Fuji and shipped them to Japan.

In addition to fieldwork, we explored climate change over timescales of decades in the Dome Fuji region. Because long-term near-surface temperature observations are restricted to Dome Fuji in East Antarctica, we created a dataset of monthly mean near-surface temperatures for the interior of East Antarctica. Owing to harsh climate conditions, the observed data are fragmentary and far from near-continuous. Thus, in this study, we reconstructed continuous temperature records using adjusted temperature data from the 2-m temperature (T-2m) of ERA5 reanalysis data. Figure 1 shows the reconstructed temperature records at the four stations in the interior of East Antarctica. The year-to-year variability at the three stations in the Dome Fuji region was similar. The surface temperature from 1999 to 2021 experienced a statistically significant warming trend at all three stations. However, surface warming did not occur during any season. The strongest warming occurred in the austral spring (September, October, and November) followed by the austral summer (December, January, and February). Except for spring and summer seasons, there was no significant trend. Previous studies based on statistical methods to reconstruct temperature records have reported that statistical warming has not started in the interior of East Antarctica. However, in contrast to previous studies, we reported that significant warming has begun, particularly in the austral spring. This implies that the atmospheric circulation that transports cosmogenic isotopes from the upper atmosphere may be changed, which may significantly influence the temporal ^{10}Be and ^{3}HHO variations in the snow samples. In the fiscal year of 2023, we will explore the impact of climate change on the ^{10}Be and ^{3}HHO records in snow samples collected at Dome Fuji.



Time series of annual mean surface air temperature in the interior East Antarctica.