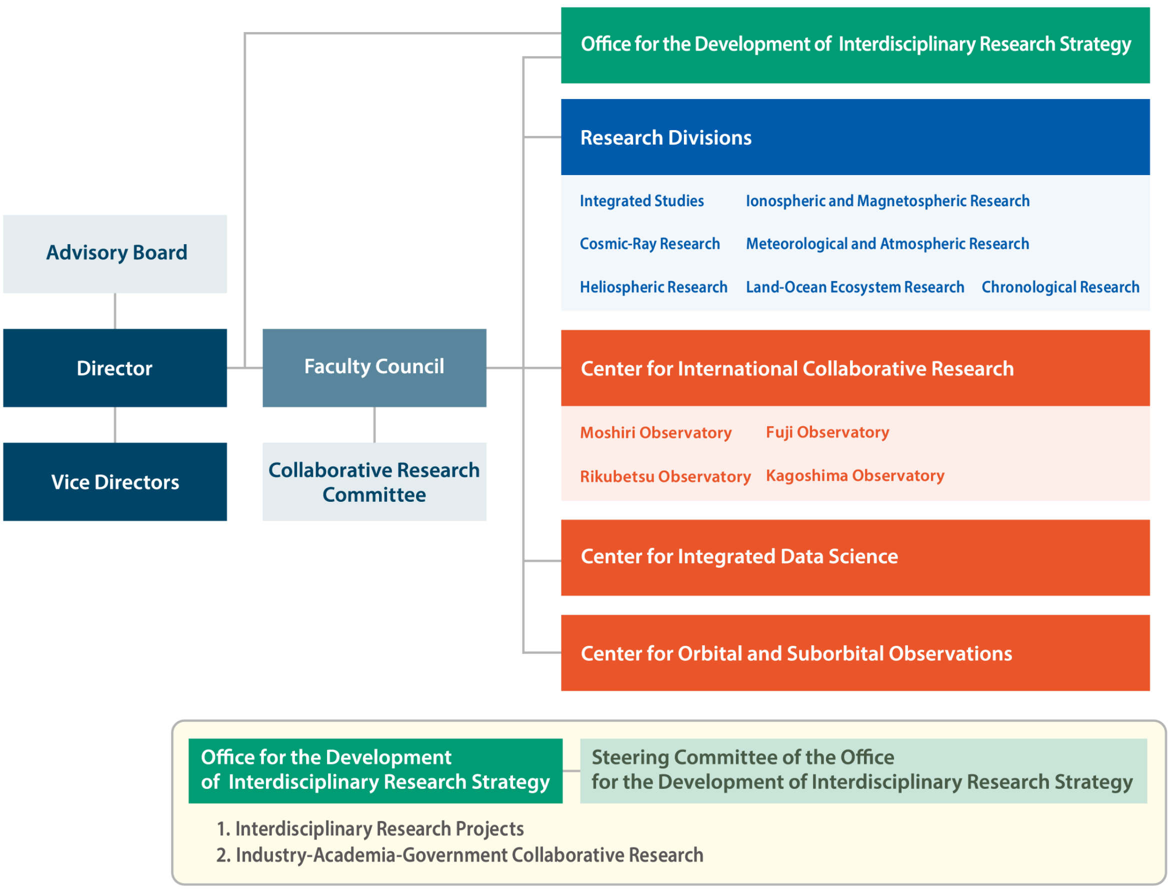
Office for the Development of Interdisciplinary Research Strategy

One of the major objectives of the ISEE is to encourage the development of new interdisciplinary research by merging Space and Earth sciences. It was established by August 2022 the Office for the Development of the Interdisciplinary Research Strategy (ODIRS). The ODIRS will promote interdisciplinary studies in cooperation with scientists in related fields based on their specialties in diverse ISEE research topics. Additionally, the ODIRS office will also benefit from the ISEE's involvement as a joint usage/research center. This will facilitate the promotion of interdisciplinary research in numerous institutions and faculties, both inside and outside Nagoya University.

The ODIRS staff comprises the Director and Deputy Director of the Institute, the directors of three affiliated centers, and a foreign faculty member from the Center for International Collaborative Research. Additionally, and two designated faculty members were recruited to serve concurrently in the ODIRS starting April 2023. The ODIRS also has a steering committee comprising faculty members from the related Departments of Nagoya University and some external members. The Committee is working to formulate a new strategy for interdisciplinary research encompassing a vast range of fields.

Additionally, in 2022, under the leadership of the Institute's Director (General Manager), the following four projects were promoted:

1) Energetic Particle Chain -Effects on the Middle/Lower Atmosphere from Energetic Particle Precipitations-
2) Direct Search for Dark Matter with Paleo-detector
3) Data Rescues of the Analog Observational Records for the Past Solar-Terrestrial Environment
4) Changes in Surface Temperature at Dome-Fuji in East Antarctica from the Mid-Twentieth Century and the Impact of Solar Activity



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.

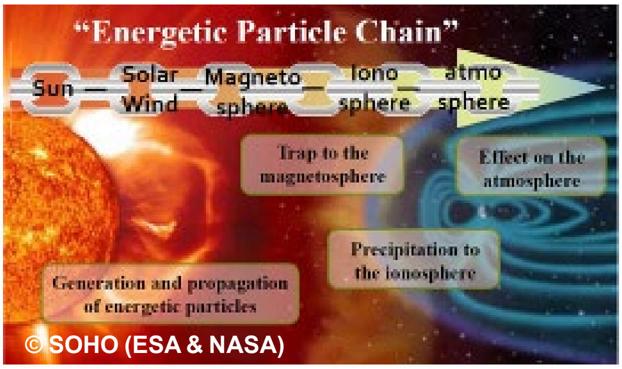


Fig.1: Image of a causal chain reaction system.

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.

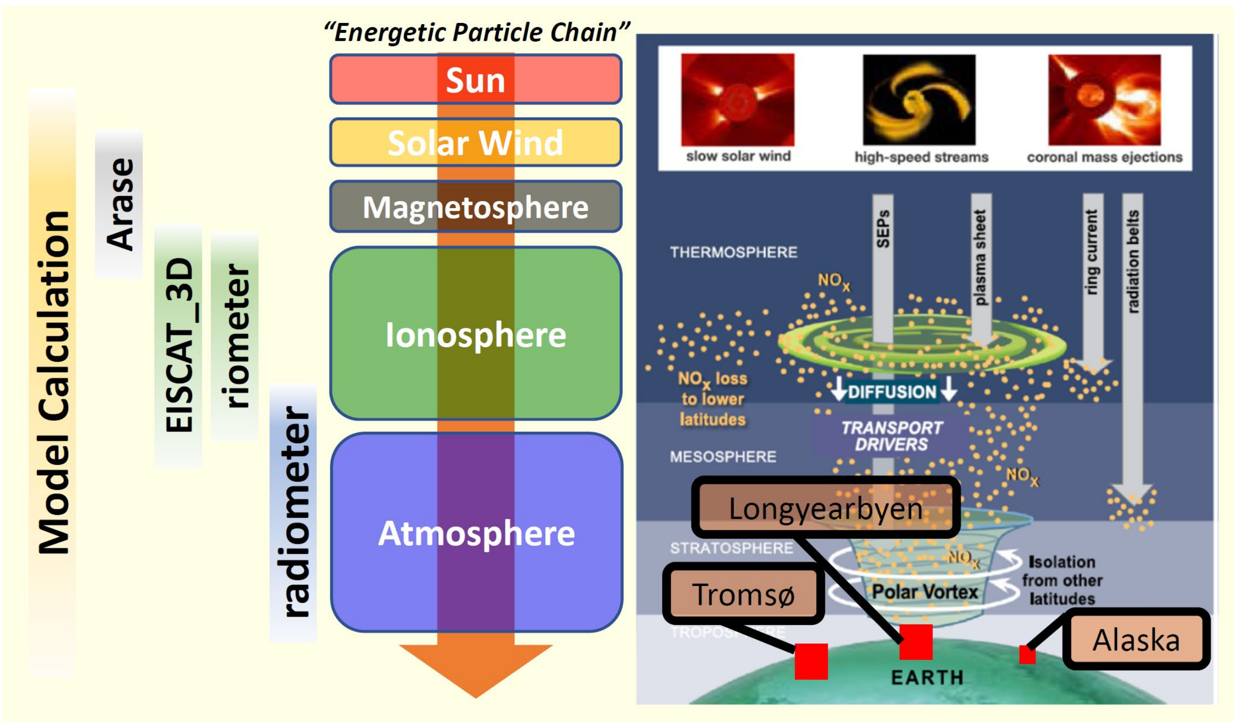


Fig.2: (left side) Observational region with each instrument and data fusion with simulation. (right side; modified from Marshall et al., 2020) Relationship between the energetic particle precipitations and new observation sites.

Main Activities in FY2022

Organization of international consortium

We have begun collaborative studies on model computations and ionospheric observations at the University of Oulu and the Finnish Meteorological Institute (FMI) in Finland. To model the middle atmosphere change due to EPPs, we invited Prof. Pekka Verronen in FMI as a visiting professor at ISEE from February to May 2023. Additionally, we have tried a new challenge to investigate the effect of EPPs on the lower atmosphere, which is the troposphere and ground-level environment, to further extend the Energetic Particle Chain. Researchers from the Divisions for Land Ocean Ecosystem, Cosmic-Ray, and Ionospheric and Magnetospheric Research were included as consortium members.

Development of a simulation code for electron precipitation

We have extended a model of wave-particle interaction - optical auroral emission - Cosmic Noise Absorption (CNA) computation to 1) compute scattering by quasi-linear wave-particle interaction due to ambient whistler-mode waves using stochastic differential equations, and 2) implement a method to compute nonlinear scattering and contribution to the electron precipitation when the magnetospheric chorus wave amplitude is increased. The results demonstrated that nonlinear wave-particle interactions, called phase trapping and dislocation, demonstrate different electron dynamics than those expected from the quasi-linear approach.

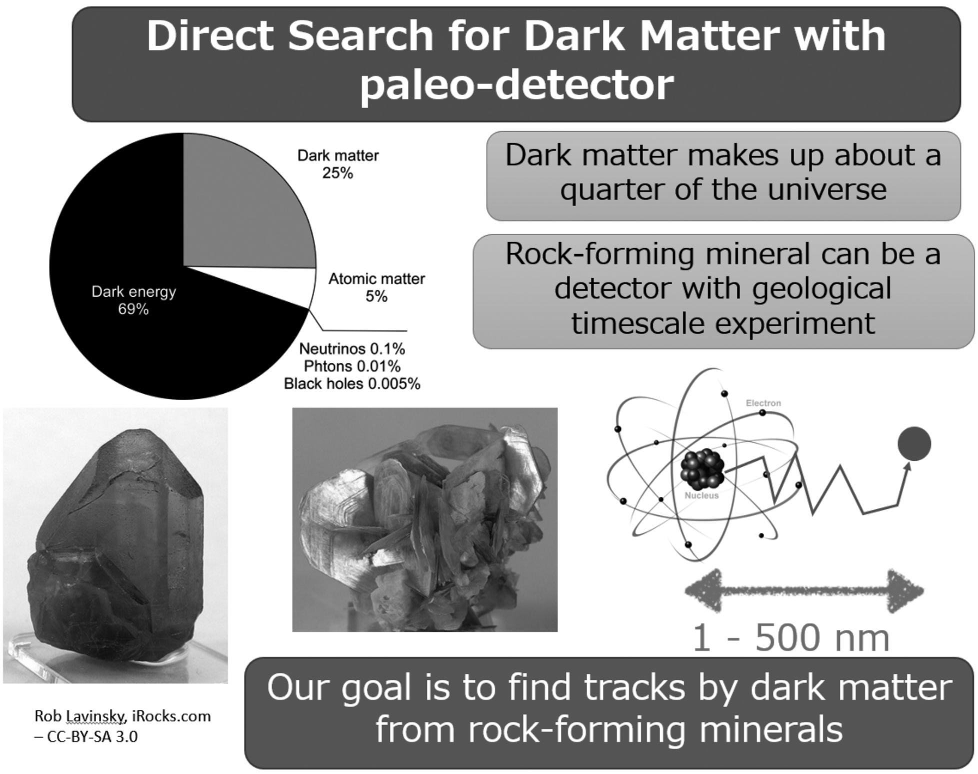
Simultaneous multi-line observation of minor constituents using a new mm-wave spectral radiometer

A researcher at Mizuno Lab attended the 63rd Japan Antarctic Research Expedition and stayed at Syowa Station until February 2023. Using a new mm-wave spectral radiometer equipped with a newly developed multifrequency receiver system, the simultaneous observation of five molecular species, O_3, NO, NO_2, HO_2, and CO, started. For NO, which is a key molecule for understanding ion chemistry, six hyperfine lines could be obtained simultaneously, and the S/N ratio was successfully improved by taking an average of the six lines. There have been no simultaneous observations of these six NO hyperfine lines worldwide, which is a unique achievement of this study.

- We estimated the pitch-angle diffusion coefficient derived from the Arase observations. Compared with the energy spectrum derived from EISCAT observations, we demonstrated that the observed chorus waves cause wide-energy electron precipitation if the waves propagate to higher latitudes along the magnetic field line.
- The LAMP sounding rocket experiment was performed in Alaska in March 2022 and demonstrated the precipitation of relativistic electron microbursts associated with pulsating auroras, as predicted by the Miyoshi et al. (2020) model.
- A spectral riometer was deployed in Kilpisjärvi, Finland, and the observations began in October 2022. This observation was performed simultaneously with the EISCAT radar and captured ionization in the lower ionosphere, which showed CNA increases by energetic electron precipitation. An increase in CNA during a geomagnetic storm event on February 26, 2023, was also successfully observed.
- In the temporal variation of NO due to electron precipitation, a steep rise and slow decline in the NO column density were observed a few times, particularly during winter and early spring. These features may reflect the difference in the NO production timescales by ion chemistry and NO dissociation by photochemistry, and the fact that the photodissociation timescale becomes shorter with increasing daylight hours toward the summer. Time series data obtained by the mm-wave spectral radiometer were compared with the results of the global chemical-climate model WACCM and ion chemistry model SIC in detail.

Direct Search for Dark Matter with Paleo-Detectors

Dark matter constitutes approximately one-quarter of the universe. The formation of galaxies, stars, and other large-scale structures is essential. However, they cannot be observed optically, and their true nature remains obscure. If the true nature of dark matter is revealed, it will provide important insights into new physics beyond Standard Theory, and the birth and history of the universe. Diverse attempts have been made worldwide to determine the nature of this unknown matter. For example, XENONnT uses tonnes of liquid xenon in a direct search, such as XENONnT, the detection sensitivity is limited by the product of the mass of the detector and the experimental time. This time cannot be extended indefinitely in human experiments, and liquid xenon methods have reached their scale limits. The scale limits have led to a focus on using minerals as detectors, a technique known as 'paleodetectors.' Minerals interact with dark matter at geological scales and can, therefore, be treated as detectors with extremely long experimental times. This suggests the possibility of searching for dark matter in small sample volumes with a sensitivity that exceeds that of scintillation methods that use liquid xenon. This project aims to combine petrology, geochronology, particle astrophysics, X-ray spectroscopy, electron microscopy, and analytical chemistry in collaboration with researchers from within and outside the ISEE to directly search for dark matter and other unknown elementary particles using paleodetectors. The direct search for unknown elementary particles by paleodetectors has a long history, starting with the search for magnetic monopoles using white mica in the 1980s. In 1995, Snowden-Ifft et al. attempted to search for dark matter directly using mica. However, none of these studies led to the discovery of unknown elementary particles. In recent years, paleodetectors have attracted attention, and diverse research groups worldwide have performed theoretical investigations and experiments to prove this principle. In our project, researchers from petrology, geochronology, particle physics, electron microscopy, geochemistry, and analytical chemistry work towards a proof of principle. In collaboration with other national and international research groups, we directly searched for dark matter using the latest findings from each field.



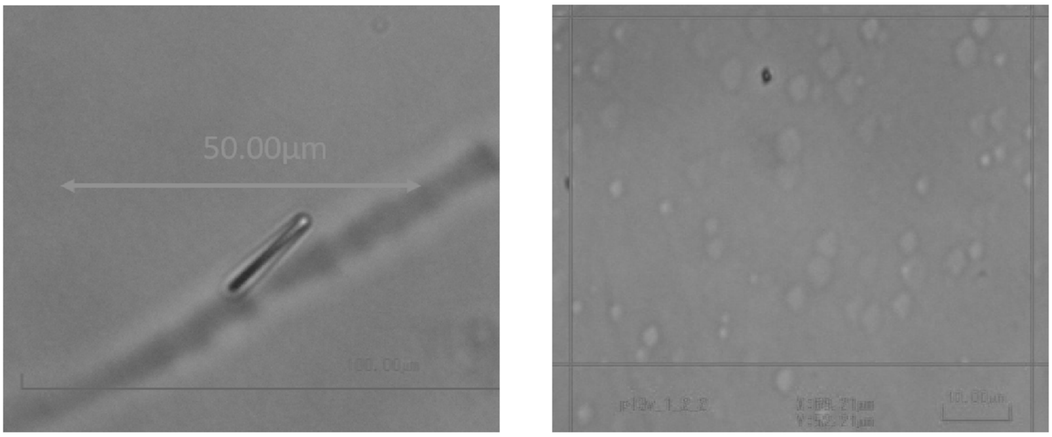
Direct search for dark matter using paleodetector.

Main Activities in FY2022

Development of a white mica track reading method

Weakly Interacting Massive Particles (WIMPs) and Q-balls are possible candidates for dark matter. The goal of this study was to establish a track detection method using olivine and muscovite for both possibilities. In FY2022, we established a plan to detect tracks using the dark matter in rock-forming minerals. Based on previous research, we focused on muscovite, which is easy to use in the search for Q-balls, where the search volume is determined by area rather than volume and where we can expect to observe tracks in both regions where the electronic stopping power is dominant and tracks in regions where the nuclear stopping power is dominant. Muscovite has distinct cleavages and can be thinly peeled. Therefore, it is possible to obtain several samples from a single mineral particle and perform large-area observations. The observation of the sample using both transmitted and reflected light is also possible. Furthermore, it is known that there are fission tracks, which occur in regions where electronic stopping power is dominant, and α-recoil, which occurs in regions where nuclear stopping power is dominant. This makes them suitable for verifying whether automated optical readings can discriminate between the two.

To verify whether the particles left a track on white mica, a heavy-ion cancer therapy machine (HIMAC) from the National Institute of Quantum Science and Technology (NIST) was used to irradiate the sample with Fe at 500 MeV/n. Post irradiation, the white mica samples were etched with hydrofluoric acid and observed under an optical microscope; clear tracks were observed. Tracks due to α-recoil, which existed before irradiation, were also observed simultaneously. This suggests the possibility of distinguishing and simultaneously observing the tracks produced in regions where the electronic stopping power is dominant from those produced in regions where the nuclear stopping power is dominant.



Photomicrograph of fission track (left) and α recoil track (right).

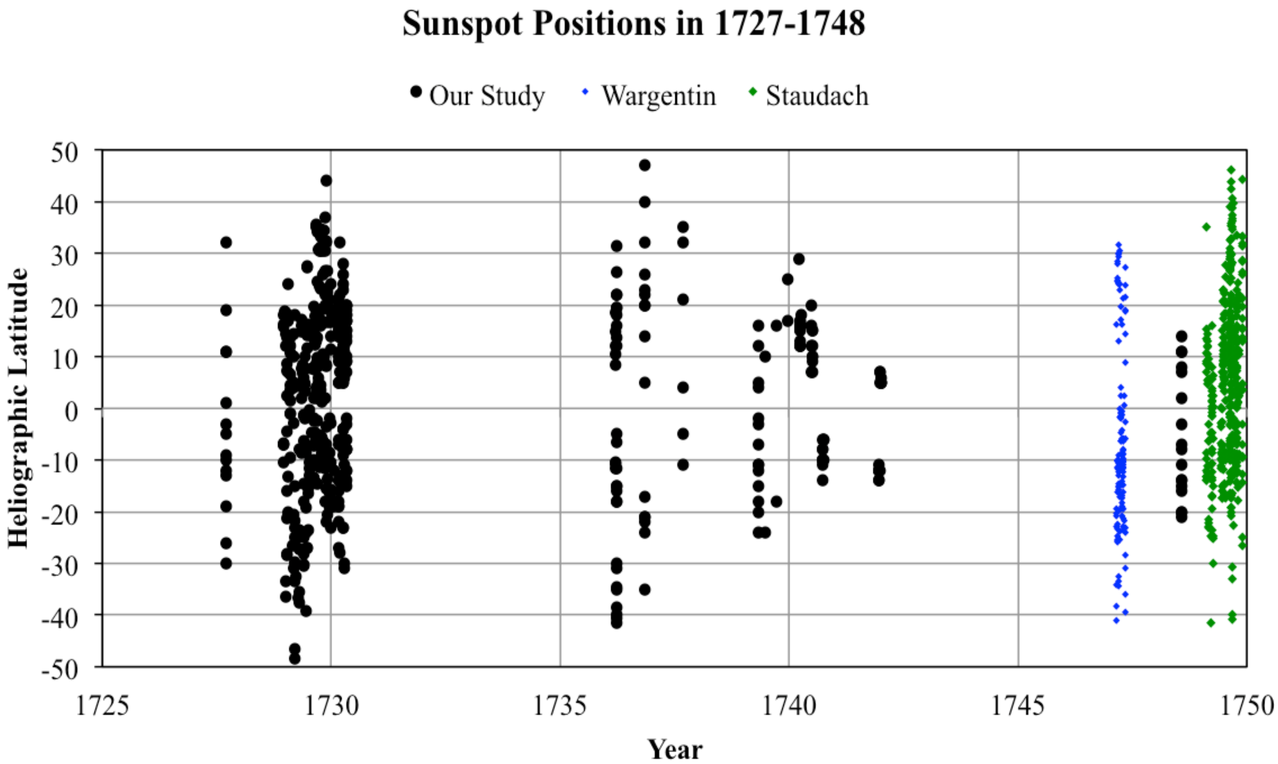
Initiatives for collaboration between research institutions

In recent years, diverse groups have attempted direct searches for dark matter and neutrino detection using minerals. In FY2022, our group and the JAMSTEC group held three joint meetings to report on their status and discuss the situation, strengthening collaboration towards the realization of direct dark matter searches.

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

Since the beginning of the space age (1957), modern civilization has continuously developed technological infrastructure and conducted space explorations, increasing our understanding of the solar–terrestrial environment. In this context, it is known that extreme solar storms seriously impact satellites, power plants, and power grids. In this regard, it is important for us to prepare to protect our civilization from such space weather hazard.

The solar–terrestrial environment is analyzed based on observational datasets. However, such datasets were systematically developed only for the International Geophysical Year (1957–1958). Such a short timespan (66 years) is one of the major limitations to studying infrequent extreme solar storms and long-term solar variability. Our project aims to overcome these difficulties by preserving, organizing, and recalibrating the data in past analog records, and quantitatively reconstruct past solar activity and geomagnetic disturbances on their basis. In this fiscal year, we have made significant advances in analyses on sunspot records and solar coronal records. The most significant results are briefly summarized below.



Sunspot positions in 1727–1748 (Hayakawa et al., 2022a, The Astrophysical Journal, 941, 151). This result has revealed previously undocumented sunspot positions in 1727–1748 and verified regular solar cycles between the Maunder Minimum (1645–1715) and the SILSO monthly database (1749 onward).

Main Activities in FY2022

Our team collected and analyzed old analog datasets for past solar-terrestrial environments and reconstructed the long-term variability and extreme events of the heliosphere, cosmic rays, ionosphere, and magnetosphere. In this fiscal year, our team has significantly developed research on the long-term variability of the terrestrial environments with considerable media exposure, as summarized below.

Our team has developed analyses of sunspot and eclipse records for the long-term variability of solar-terrestrial environments. Among the four centuries of solar cycles, the early 18th century and the Dalton Minimum have been considered two of the greatest fault lines for recalibration (Section 5 of Clette et al., 2023). For the former, our team comprehensively evaluated the original records of the known sunspot datasets in 1727–1748 and acquired forgotten records (e.g., Van Coesfeld, Duclos, and Martin) to revise sunspot group numbers and newly derived butterfly diagrams for this period. Our team also collaborated with the Royal Observatory of Belgium to recalibrate sunspot numbers in the 19th century and jointly published a status report for the international collaboration of sunspot number recalibration under Frédéric Clette (Clette et al., 2023, *Solar Physics*, 298, 44).

Our team has also developed evaluations of solar eclipse records to determine past solar-coronal structures. We comprehensively evaluated the great solar eclipses in Hokkaido from the 18th to 19th centuries and identified the total solar eclipse in Ainu folklore as that of 1824. This folklore account indicates probable coronal streamers despite their chronological position around the end of the Dalton Minimum. This is consistent with the 1806 eclipse account, in contrast to the Maunder Minimum without significant coronal streamers. As a by-product of our investigations of the Byzantine eclipse records, our team also revised the rotation speed of Earth in the 4th to 7th centuries. This article has especially attracted considerable media exposure, recording 403 Altmetrics, and most read and discussed in the Publications of the Astronomical Society of the Pacific.

For solar storms, our team has comprehensively evaluated solar eruptions, geomagnetic disturbances, low-latitude aurorae, and cosmic-ray variability, visualizing magnitudes of the source flare (≈ X35) and the resultant geomagnetic storms (min Dst ≈ −389 nT), auroral visibility down to Tsugaru Strait and Tajikistan, and magnetopause standoff down to ≈ 3.4 RE.

Additionally, our team comprehensively evaluated the extreme solar storms in February 1872 in terms of the contemporaneous solar surface, geomagnetic disturbance, and auroral activity. Our results verified this storm to be a Carrington-class storm. This manuscript is currently in press (Hayakawa et al., *The Astrophysical Journal*, 10.3847/1538-4357/acc6cc).

The achievements of our team have been broadcast internationally in Israel, Taiwan, the US, and Finland. One of our results from the previous FY was extensively broadcast and recorded Altmetrics of 351. Our team's achievements have been broadcasted in the NHK too – "Cosmic Front and Hokkaido Do."

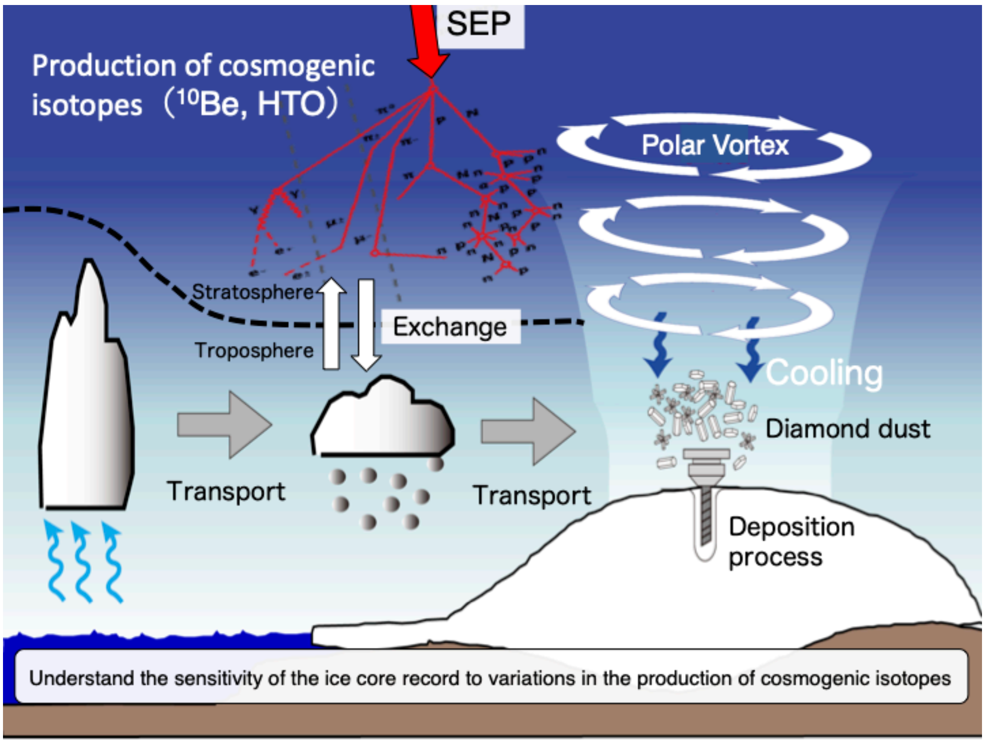
Additionally, the team PI joined a guest editorial board for the special issue in the Geoscience Data Journal, accommodating four data papers, six data service papers, two reviews, and one invited article. As such, data rescue activities have accelerated not only at Nagoya University but also worldwide.

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

Human society has become more sophisticated, and changes in the space environment have significantly impacted social life. For example, a solar eruptive event in 1989 caused several satellites to fail and generated severe magnetic storms. The 2017 solar eruptive event affected the Global Positioning System (GPS) and increased positioning errors. Solar activity is constantly monitored using satellites and space weather forecasts have been initiated. However, our knowledge of solar eruptive events is limited because our observational history encompasses only a few decades and excludes extreme events. To improve our understanding of solar events and their future predictability, it is essential to reveal the long-term history of solar eruptive events using a paleo-proxy method.

Past intense solar eruptive events are thought to have been recorded as positive anomalies of cosmogenic isotopes (e.g., ^{10}Be) in paleoarchives, such as ice cores. The cosmogenic isotope method is extensively used to detect past extreme solar events. The extreme solar events that occurred in 774 and 993 AD were recorded as abnormal ^{10}Be peaks in the ice core records. However, it is well known that there is uncertainty in the strength of these events reconstructed using the cosmogenic isotope method. This is because the cosmogenic isotopes archived in the ice cores reflect not only changes in the production of cosmogenic isotopes in the upper atmosphere, but also the transport and deposition processes at the site. Therefore, to reconstruct the strength of past solar eruptive events, it is essential to comprehend the sensitivity of ice core records in terms of variations in the production of cosmogenic isotopes in the upper atmosphere.

In this study, we attempted to estimate the sensitivity of the cosmogenic isotope method for detecting extreme solar eruptive events by collaborating across diverse disciplines including solar physics, geo-electromagnetics, meteorology/climatology, and glaciology. Currently, we are focusing on the East Antarctic region to elucidate the process of recording cosmogenic isotopes (^{10}Be and HTO) in ice cores.



The objectives and research topics of the project.

Main Activities in FY2022

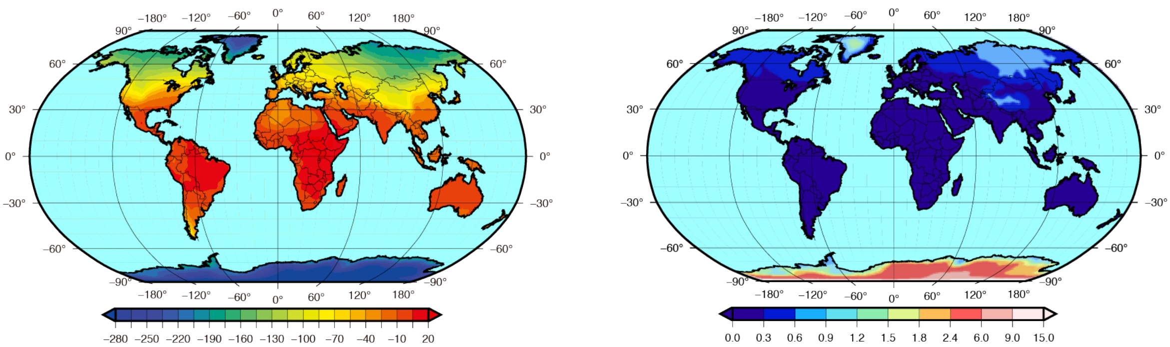
Antarctic field observation “Quantitative evaluation of solar eruptive events detected in cosmogenic nuclides of ice core”

We joined the 64th Japanese Antarctic Research Expedition (JARE) and performed a field research program entitled “Quantitative evaluation of solar energetic storms detected in cosmogenic nuclides of ice core (Principal Investigator: Naoyuki Kurita)”. The purpose of this study is to elucidate the mechanism by which variations in the production of cosmogenic isotopes in the upper atmosphere have been recorded as positive anomalies in isotope proxy records. In this fiscal year, we performed shallow ice core drilling at two sites along the route to Dome Fuji: H15 site, 50 km inland from the coast (observation period: December 22–31, 2022) and site H128, 100 km inland from the coast (observation period: January 4–15, 2023). The ice samples collected were 35 m deep at site H15, representing snow deposited after the 1900s, and 26 m deep at site H128, representing snow deposited approximately 150 years ago. Since it is difficult to collect near-surface snow samples using drilling techniques, surface snow samples were also corrected at 3 cm intervals from the snow pit at a depth of 1.5 m at H15 and 3.0 m at H128. The collected samples were stored in cardboard boxes and shipped back to Japan under frozen conditions.

Left: Observation field at H128 site. Right: Shallow ice core drilling at H15.

The global distribution of natural HTO in precipitation simulated with 3-D water transport model

We developed a global atmospheric water transport model to evaluate Antarctic observational data. The model incorporates a water isotopologue scheme into an atmospheric circulation model forced by reanalysis data. The production of cosmogenic tritium was obtained from a simulation combining the computed neutron and proton spectra with yield function techniques. The simulated natural HTO distribution reproduced the observed data well and is expected to be useful for elucidating the transport of cosmic-ray-produced nuclides to the Antarctic ice sheet.



Left: Simulated global HDO distribution in precipitation. Right: Simulated global HTO distribution in precipitation.