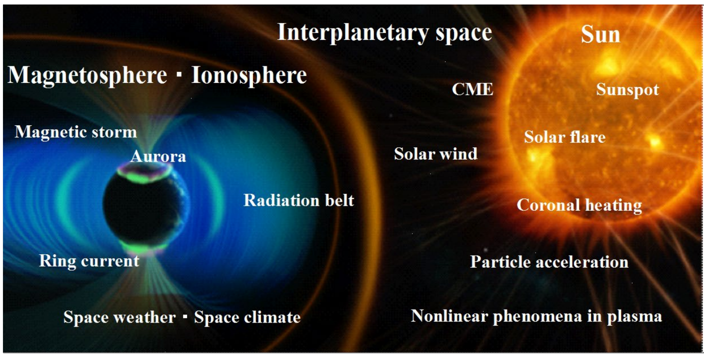
Division for Integrated Studies



- Solar flare · CME
- Inner magnetosphere · Radiation belt
- Aurora substorm
- Space weather · Space storm
- Space climate · Long-term variations of the Sun
- Space plasma
- Computer simulation
- Data assimilation

In the Division for Integrated Studies, we conduct scientific research aimed at the comprehensive understanding and prediction of various phenomena in the solar–terrestrial system based on advanced computer simulations and data analyses. In particular, we promote studies to elucidate various phenomena, such as solar cycles, solar flares, coronal mass ejections (CMEs), geomagnetic storms, and aurora, where the nonlinear interaction and intercoupling between different systems play an important role. We also promote scientific projects of satellite missions (Hinode and ERG satellites) by observing the Sun and geospace in cooperation with the Institute of Space and Astronautical Science (ISAS)/JAXA, and the National Astronomical Observatory of Japan (NAOJ). The faculty members of this division are responsible for education in the Graduate Schools of Science and Engineering at Nagoya University.

Main Activities in FY2020

The first physics-based method for predicting large solar flares

Because large solar flares can cause severe space weather disturbances affecting the Earth, their occurrence must be predicted to mitigate their impact. The research team led by Professor Kanya Kusano succeeded in developing the first physics-based model to accurately predict imminent large solar flares. The predictive model was tested on active regions during solar cycle 24 from 2008 to 2019. With few exceptions, the new model predicted the most imminent solar flares and the precise location from which they will emerge. The researchers also discovered that a new parameter – the "magnetic twist flux density" close to a magnetic polarity inversion line on the solar surface – determines when and where solar flares probably occur and how large they are likely to be. This research was published in the journal *Science* on July 31, 2020 (Kusano et al., *Science*, 2020).

Exploring the HSP in solar cycle 24

Over the past decades, extensive solar observations have revealed that left-handed/right-handed helical structures appear more frequently in the northern/southern hemisphere of the Sun, independent of the solar cycle. This is the so-called hemispheric sign preference (HSP) of helicity. By analyzing the magnetic helicity flux in solar active regions (ARs), we found that 63% and 65% of the investigated AR samples in the northern and southern hemispheres, respectively, followed the HSP. The HSP gradually increases from 50%–60% up to 70%–80% for AR samples, which (1) appear at the earlier rising phase of solar cycle 24 or higher latitudes, and (2) have larger values of the total unsigned magnetic flux and the average plasma flow speed. Our observations support the enhancement of the HSP mainly by the Coriolis force acting on an expanding flux tube through the convection zone, and the differential rotation on the solar surface and alpha effect at the base of the convection zone. Future research should employ advanced solar convective dynamo simulations to investigate the HSP trends found in this study and use them for model validation (Park et al., *ApJ*, 2020).

Data-driven MHD simulation of successive solar plasma eruption

To predict solar flares and plasma eruptions with a physical understanding, the magnetic field information from the photosphere (the surface of the Sun) to the corona (the upper plasma atmosphere) is necessary. The photospheric vector magnetic fields were observed in detail, whereas the coronal magnetic fields can not be measured. Many numerical methodologies for inferring coronal magnetic fields have been developed together with an increase in the quality of photospheric magnetic data for decades. In this study, we developed a method of data-driven magnetohydrodynamic (MHD) simulation in which time-series observational data of the photospheric magnetic fields were incorporated in the bottom boundary condition of the MHD simulation. Using this method, the response of the coronal magnetic fields to the temporal evolution of the photospheric magnetic fields was reproduced. We demonstrated the feasibility of the newly developed data-driven method by reproducing successive solar plasma eruptions during an observation (Kaneko et al., *ApJ*, 2021).

Solar cycle-related variation in solar differential rotation and meridional flow in solar cycle 24

Predicting the next solar cycle is crucial for space weather studies. So far, we have developed the suface flux transport (SFT) code to predict solar cycle activity and improve the accuracy of the parameters necessary for SFT calculation. We concentrated on obtaining the velocity field, which is a necessary parameter for this model calculation, using satellite observations, and found that the flow in the meridional plane in solar cycle 24 was faster than that in cycle 23 (Imada et al., *Earth, Planets and Space*, 2020).

Reconstructions of the past solar–terrestrial environments with historical documents and analog records

To assess the long-term variability of solar–terrestrial environments, historical documents and analog records allow us to chronologically extend the insights of modern observations. Therefore, we are working on the quantitative reconstructions of short-term space weather events and long-term solar variability by analyzing their relevant historical records. During this fiscal year, we analyzed the extreme space weather events in October/November 1903 (Hayakawa et al., *ApJL*, 2020c), January 1938 (Hayakawa et al., *ApJ*, 2021b), February/March 1941 (Hayakawa et al., *ApJ*, 2021a), and March 1946 (Hayakawa et al., *MNRAS*, 2020d) to reconstruct their solar surface and temporal evolution and quantitatively evaluated the magnitude of the geomagnetic disturbances. We also analyzed the sunspot group number and solar coronal structure for long-term solar variability and contrasted the Maunder Minimum and Dalton Minimum (Hayakawa et al., *ApJ*, 2020b; Hayakawa et al., *ApJ*, 2020e; Hayakawa et al., *MNRAS*, 2020f; Silverman and Hayakawa, *JSWSC*, 2021).

Relativistic electron microbursts as high-energy tail of PsA electrons

We showed that subrelativistic/relativistic electron microbursts form the high-energy tail of a pulsating aurora (PsA). Whistler-mode chorus waves that propagate along the magnetic field lines at high latitudes cause precipitation bursts of electrons with a wide energy range from a few keV to several MeV (relativistic microbursts). The rising tone elements of chorus waves cause individual microbursts of subrelativistic/relativistic electrons and PsA internal modulation at a frequency of a few hertz. The chorus bursts for a few seconds, causing the microburst trains of subrelativistic/relativistic electrons and the main PsA pulsations. Our simulation studies demonstrated that both PsA and relativistic electron microbursts originated simultaneously from pitch angle scattering by chorus wave–particle interactions along the field line (Miyoshi et al., *GRL*, 2020).

Very high altitude auroral acceleration region captured by Arase-THEMIS/ASI conjugate observation

We found a very high altitude auroral acceleration region extending beyond 30000 km altitude using comprehensive particle and field observations (including a high-angular resolution electron detector LEP-e) with the Arase satellite and a THEMIS ground-based imager. This finding challenges the conventional view in which the auroral electron is mostly accelerated at altitudes of a few thousand kilometers, and brings new mysteries of auroral emission mechanisms. Understanding the detailed properties of the very high altitude auroral acceleration region is crucial for following the processes of discrete auroral emission on other planets and electron acceleration on extraterrestrial magnetospheres such as pulsars (Imajo et al., *Scientific reports*, 2021).

Effects of the IMF By on ring current asymmetry under southward IMF Bz conditions observed at ground magnetic stations: Case studies

The ring current is asymmetric during the main phase of a geomagnetic storm. In this study, we evaluated the role of the IMF By on the asymmetry of the ring current during the main phase of geomagnetic storms. To evaluate the ring current asymmetry, the mean H variations were calculated using 31 ground magnetic stations over magnetic latitudes of 9–45°. Further, the magnetic local time (MLT) variations in the H-component at these stations regarding the mean H were investigated for three cases of geomagnetic storms with varying southward interplanetary magnetic field (IMF) Bz and IMF By conditions. The primary role of IMF Bz on the asymmetry of the ring current was observed. For the first time, this study examined the additional role of IMF By in influencing the MLT distribution of the ring current at ground magnetic stations. Under southward IMF Bz conditions, based on the Super Dual Auroral Radar Network (SuperDARN) and the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) observations, IMF By altered the MLT distribution of the ring current under suitable conditions. The timescales of the IMF By also play a very important role in determining the asymmetry of the ring current. Under a steady convection state, the IMF By could rotate the convection cells based on its polarity, which changed the MLT distribution of the ring current observed at low-latitude ground stations. Thus, this study highlights the important role of IMF By on the asymmetric MLT distribution of the ring current under the southward IMF Bz (Kumar et al., *JGR*, 2020).

Tracking the source of the near-Earth plasma sheet

Recent research has used Arase data to determine how the composition of the plasma sheet changes during a storm. The contributions of ionospheric and solar wind to the magnetosphere can be determined by their composition. While both sources contain significant H^+ ions, the heavy ion species from the ionospheric source are generally singly ionized, whereas the solar wind heavy ions are highly ionized. Using composition data from multiple satellites, we tracked how the source of the plasma sheet changed during a storm. An initial study using Active Magnetospheric Particle Tracer Explorers (AMPTE)/Charge-Energy-Mass Spectrometer (CHEM) data, a dataset that included the full charge state distributions of major species, showed that the transition could occur quite sharply during storms, with the ionospheric contribution becoming dominant during the main storm phase (Kistler, 2020). However, during the AMPTE period, there were no continuous measurements of the upstream solar wind, and thus both the simultaneous solar wind composition and the driving solar wind and IMF parameters were not known. Using the LEPi and MEPi instruments on Arase, we used the He^{++}/H^+ ratio compared to that in the solar wind to determine the solar wind contribution. This allowed the determination of the ionospheric contribution to the H^+ population to measure the full ionospheric contribution. When the IMF turned southward during the main storm phase, the dominant source of the hot plasma sheet became ionospheric. This composition change explained why the storm-time ring current also had a high ionospheric contribution (Kistler, *GRL*, 2020).

Atomic oxygen ion-neutral collision frequency in the F-region ionosphere

The collision between atomic oxygen and its first positive ion plays a major role in the ionosphere of the Earth's F-region. An accurate corresponding collision frequency model is required to quantitatively understand the ionosphere. However, the widely used classic Banks theoretical model typically provides a collision frequency that is 30% lower than the expectation from ionospheric observations. Accordingly, the classic collision frequency is often adjusted by multiplying it by a constant known as the Burnside factor. This correction-factor model adopted the classic model as its basis because of the misunderstanding that the classic model was based on a laboratory experiment; that is, the correction factor was originally meant to compensate for laboratory contamination. In this study, a collision frequency model was constructed based on a laboratory experiment, and the resultant laboratory-based model was found to be consistent with ionospheric observations. In this construction, the impact of laboratory contaminations was determined to be small (7%) and was mostly canceled by misinterpreting conventional definitions of energy. Thus, the 30% difference was mainly caused by a theoretical error in the classic model. This error was energy-dependent and corrected using a later wide-energy theoretical model. Thus, the classic model could not be corrected by a temperature-independent constant and should be replaced by a later model (Ieda, *JGR*, 2021).

Ionospheric plasma density oscillation related to EMIC Pc1 wave

Based on the Swarm satellite observations, Kim et al. presented the first observational evidence of ionospheric plasma density oscillations coherent with electromagnetic ion cyclotron (EMIC) Pc1 waves. They compared the amplitudes of the density and magnetic field oscillations based on the MHD theory and found that the density power was much larger than the magnetic field power (Kim et al., *GRL*, 2020).

A novel calibration method for waveform signals and its application to Arase/PWE observations

Waveform data passing through a system comprising sensors, amplifiers, and filters should be calibrated in the frequency domain for use as scientific data. However, waveform data calibrated by conventional methods are distorted in the time domain when using a short-time window. To perform an accurate calibration with a short-time window, we proposed a novel calibration method to estimate the phase shifts of a window function from the gradient of a transfer function and remove the distortion by dividing the data by the shifted window functions at each frequency in the time domain. We applied this method to actual electric field data detected using plasma wave experiment (PWE)/waveform capture (WFC). Consequently, the proposed method reproduced seamless waveforms with 1% errors of the wave amplitude. We are currently applying for a patent using this novel calibration method (Japanese patent application number: P2020-206843).

In addition to the above topics, the following studies were conducted in FY 2020

- Statistical analysis of ion heating by EMIC waves via the wave–particle interaction method: Arase observation
- Characteristics of EMIC waves in the magnetosphere based on Van Allen Probes and Arase observations
- Spatio-temporal evolution of energetic electron injection in the inner magnetosphere observed by Arase and Van Allen Probes satellites
- Analyses of drift echo holes using the Arase satellite and ground-based observations