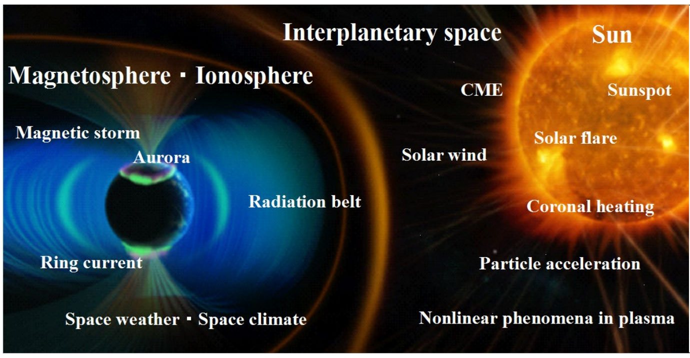
Division for Integrated Studies



- 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 FY2021

Reconstructions of the past solar-terrestrial environments with historical documents and analog records

Analog records and historical documents are of vital importance to chronologically extend our scientific knowledge of the extremity of the solar-terrestrial environment. Our team exploited historical records of solar storms and long-term solar variability. In the fiscal year 2021, we quantitatively analyzed and reconstructed the solar storms in September 1859, March 1940, and the International Geophysical Year (1957–1958) based on reports on solar eruptions, geomagnetic disturbances, and low-latitude aurorae. For the long-term solar variability, we analyzed the sunspot observations of Prantner in the Dalton Minimum and those of Fogelius, Siverus, and Müller around the Maunder Minimum (Hayakawa et al., *MNRAS*, 2021 and 2022; *GDJ*, 2022; *ApJ*, 2021 and 2022; *PASJ*, 2021; *Solar Physics*, 2021).

The solar differential rotation was reproduced for the first time with the highest resolution simulation with supercomputer “Fugaku”

Associate Professor Hideyuki Hotta (Graduate School of Science, Chiba University) and Professor Kanya Kusano (ISEE) succeeded in precisely reproducing the thermal convection and the magnetic field in the solar interior in the super high-resolution calculation on supercomputer “Fugaku.” As a result, the basic structure of the solar differential rotation, that is, the equatorial region rotates faster than the polar region, was reproduced based on the first principle of magnetohydrodynamics without any artificial manipulation. The powerful computational ability of “Fugaku” enabled us to resolve the Sun with 5.4 billion grid points and reproduce the differential rotation on the computer. Because the differential rotation of the interior of the Sun is believed to be the main cause of sunspot formation, this result will be a big step toward solving the mystery of the 11-year solar cycle (Schwabe cycle), which is one of the biggest problems in astronomy (Hotta and Kusano, *Nature Astronomy*, 2021).

New numerical method to model the energy loss from solar corona

Most of the energy of the solar corona is lost in the atmospheric layer, which is known as the transition region. The transition region tends to be extremely thin owing to the sharp temperature dependence of thermal conduction and radiative cooling. A large number of grid points are required to fully resolve this thin layer and accurately model the energy loss from the solar corona. We proposed a new numerical method to model the energy loss from a solar corona. In this method, the transition region was numerically broadened while maintaining the energy balance between thermal conduction and radiative cooling. This method enabled us to model the transition region with a grid size of 50–100 km, which is approximately 1000 times larger than the physical requirement. In other words, we can reduce the computational cost of the 3-D atmospheric model by a factor of 1 trillion (Iijima and Imada, *ApJ*, 2021).

Study of coronal heating mechanism based on statistical analysis of occurrence frequency distributions of solar flares

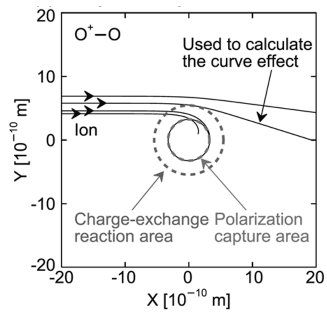
In conventional corona heating research, the contribution of nanoflares, which cannot be identified by observation, is not sufficiently considered and energy other than thermal energy is not considered when estimating the amount of flare release energy. To overcome these problems, we developed and researched a new analytical method that combined satellite observation data and numerical calculations. The results supported the validity of the nanoflare hypothesis in the active region (Kawai and Imada, *ApJ*, 2021a, 2021b, Kawai, PhD thesis, Nagoya University, 2022).

Magnetic helicity as a tool for understanding the flaring activity of the Sun

Observations of various features in the solar atmosphere revealed an interesting tendency for more left-handed helical structures in the northern hemisphere and right-handed structures in the southern hemisphere. This is the so-called hemispheric sign preference (HSP) for magnetic helicity. Recently, we examined what the HSP tells us about the long-term flaring activity of the Sun, using the solar magnetic field data observed by NASA's Solar Dynamics Observatories (SDO). As a result, we found a specific heliographic region in the Carrington coordinates correlating with the solar surface that shows an extremely low degree (approximately 40%) of HSP compliance. Interestingly, this heliographic region showed the highest flaring activity over solar cycle 24. This association of the lower HSP compliance with the higher flaring activity needs to be further examined with more AR samples and different solar cycles to understand the early formation and development of flaring active regions even in the deeper convection zone (Park et al., *ApJ*, 2021).

Curved trajectory effect on charge-exchange collision at ionospheric temperatures

Collisions between ions and neutral particles are an essential characteristic of the Earth's ionosphere. This ion-neutral collision is usually caused by the polarization of neutral particles. This collision can also be caused by charge exchange if the particle pair is parental, such as atomic oxygen and its ion. The total collision frequency is not the sum of the polarization and charge-exchange components but is essentially equal to the dominant component. The total is enhanced only around the classic transition temperature, which is near the ionospheric temperature range (typically, 200–2000 K). However, the magnitude of this enhancement differs in previous studies; the maximum enhancement has been reported to be 41% and 11% without physical explanation. In this study, the contribution of the polarization force to the charge-exchange collision was expressed as a simple curved particle trajectory effect. Consequently, the maximum enhancement was 22%. The enhancement has been neglected in classic ionospheric



Collision between an ion and parent neutral particle. The polarization collision couples with the charge-exchange collision, resulting in an enhancement of the total momentum-transfer cross section up to 25%.

studies, partly due to confusion with the glancing particle contribution, which adds 10.5% to the polarization component. This enhancement has presumably been neglected because there is no functional form to express it. This expression was derived in this study (Ieda, *JGR*, 2022).

Ozone depletion caused by high-energy electron Precipitation: Arase and EISCAT Observations

During a magnetic storm in March 2017, simultaneous European Incoherent Scatter Scientific Association (EISCAT) and optical campaign observations detected precipitation of relativistic electrons to ~3 MeV with pulsating auroras associated with omega bands. During this time interval, strong chorus waves were observed on the magnetosphere side by the Arase satellite. Simulations based on Arase observations reproduced the high-energy electron precipitation observed by the EISCAT. Furthermore, computer simulations of atmospheric chemistry showed that energetic electrons precipitated into the atmosphere cause strong ionization in the mesosphere, destroying more than 10% of mesospheric ozone. This result indicated that interactions between chorus and magnetospheric electrons cause coupling between the magnetosphere and atmosphere through the precipitation of energetic electrons (Miyoshi et al., *Scientific Reports*, 2021).

Contribution of electron pressure to ring current and ground magnetic depression using RAM-SCB simulations and Arase observations during 7–8 November 2017 magnetic storm

Geomagnetic storms are among the most important phenomena affecting Earth's space weather. Intense geomagnetic storms can cause severe damage to satellites, communication, and power transmission lines. Geomagnetic storms are primarily caused by the enhancement of the ring current. The storm time distribution of ring current particles in the inner magnetosphere depends strongly on their transport in evolving electric and magnetic fields, along with particle acceleration and loss. In this study, we investigated ring current particle variations using observations and simulations. We compared the ion (H^+, He^+, and O^+), electron flux, and plasma pressure variations from Arase observations with the self-consistent inner magnetosphere model: Ring current Atmosphere interactions Model with Self Consistent magnetic field (RAM-SCB) during the 7–8 November, 2017, geomagnetic storm. We investigated the contribution of different species (ions and electrons) to the magnetic field deformation observed at ground magnetic stations (09°–45° CGM Lat.) using the RAM-SCB simulations. The results showed that ions are the major contributor (~88 %) and electrons contribute ~12% to the total ring current pressure. It was also found that the electron contribution was non-negligible (~18%) to the ring current on the dawn side during the main phase of the storm. These results indicate that the electron contribution to the storm -time ring current is important and should not be neglected (Kumar et al., *JGR*, 2021).

Analyses of drift echo holes using the Arase satellite and ground-based observations

We analyzed "drift echo holes," in which only electrons above several hundred keV are lost from the magnetosphere owing to localized and sporadic Electromagnetic ion cyclotron (EMIC) waves. Because the drift period depends on the electron energy, the echo hole shows a clear energy dispersion and diffuses and disappears several times around Earth. A single drift echo corresponds to a localized decrease of approximately 30% in the particle flux. After the echoes were repeated, the flux of the entire radiation belt decreased by approximately 10% (Nakamura et al., *GRL*, 2022).

Statistical study of EMIC waves and related proton distributions observed by the Arase satellite

EMIC waves are considered to play an important role in controlling magnetospheric plasma dynamics. In particular, EMIC wave-particle interactions can cause the loss of energetic protons and relativistic electrons in the Earth's magnetosphere, and the scattered particles precipitate into the ionosphere, creating isolated proton auroras at subauroral latitudes (55–65 geomagnetic latitudes). To understand the coupling of EMIC waves with energetic protons in the inner magnetosphere, we performed a statistical study of proton distributions associated with EMIC waves using a 4-year *in-situ* observation obtained by the Arase satellite. We found four significantly different regions of EMIC waves with different characteristics of the energetic proton distributions, and the minimum resonance energies were different. We found that EMIC waves near the threshold of the proton cyclotron instability have left-handed polarization at the magnetic equator and the generated waves propagate to higher magnetic latitudes. Furthermore, the observed pitch-angle scattering energy range coincides with the computed minimum proton resonance energy. These observational results provide new insights into the spatial distribution of the EMIC waves.

Error estimation of electron fluxes measured by HEP instrument onboard the Arase satellite

An error estimation method for the energetic electron flux was measured using a high-energy electron experiment (HEP) instrument onboard the Arase satellite. While counting statistics are assumed for the uncertainty of raw electron counts, the count-to-flux conversion for HEP data must include deconvolution using counts taken by all energy channels. In our method, the same deconvolution was applied to the electron counts to correctly deduce the error of the measured electron flux. The results showed that the flux-to-error ratio worsened for higher energy and pitch angles closer to 0° or 180°, indicating that a longer (~ several minutes) integration time is necessary to achieve a reasonable level of flux uncertainty.

Impact of subsurface convective flows on the formation of flare-productive sunspots and energy buildup

Solar flares are caused by the release of magnetic free energy stored in sunspots. This study aimed to reveal the impact of convective flows in the convection zone on the formation and evolution of sunspot magnetic fields. We simulated the transport of magnetic flux tubes in the convection zone and sunspot formation in the photosphere using the radiative magnetohydrodynamic code R2D2 and the supercomputer Fugaku. We performed 93 simulations by allocating flux tubes to 93 different positions in the convection zone. We found a strong correlation between the distribution of magnetic free energy in the photosphere and the position of the downflow plume in the convection zone. The results suggested that high free energy regions can be predicted even before the magnetic flux appears on the solar surface by detecting the downflow profile in the convection zone (Kaneko et al., *MNRAS*, in press).

Investigation of spatiotemporal evolution of erupted solar magnetic flux rope in the inner heliosphere using multi-point spacecraft measurements

The global structure of the magnetic flux rope inside the CME plays a key role in triggering geomagnetic storms and their cascade of effects. Thus, it is important to understand how the magnetic flux rope that erupts from the Sun evolves spatially and temporally as it propagates in the inner heliosphere. We developed an analysis tool to implement 1D (or 2D) flux rope model fitting on solar eruptive magnetic flux rope events observed by multiple spacecraft to reconstruct their global topologies. We started to analyze a magnetic flux rope event observed by Venus Express (orbited Venus), WIND (upstream of Earth), MAVEN (cruise to Mars), and Mars Express (orbited Mars) in 2014 April, using the analysis tools.

Database construction of Toyokawa Radio Polarimeters

Historical data from 1958 to 1978 taken by Toyokawa Radio Polarimeters (1, 2, 3.75, and 9.4 GHz) were recorded in microfilms. All have been scanned and restored in digital image form. This database is very useful for various types of research, such as the size estimation of a solar flare in the era before GOES soft X-ray observations began and the study of the characteristics of solar flares in the old solar cycle.