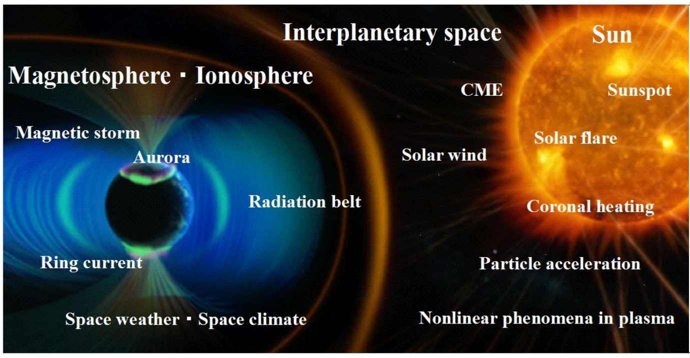
Division for Integrated Studies



- 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 FY2022

Reconstructions of the past solar-terrestrial environments with historical documents and analog records

Analog records and historical documents are of vital importance for chronologically extending our scientific knowledge of the extremities of the solar-terrestrial environment. Our team exploited historical records of solar storms and long-term solar variability. In the fiscal year 2022, our team evaluated sunspot records from 1727 to 1748, where the data were extremely scarce and revised the sunspot group number and newly derived sunspot positions in this interval. Our team exploited sunspot drawings in the Kawaguchi Science Museum and quantitatively evaluated data stability. Our team also exploited eclipse records to evaluate rotational variability of Earth in the 4th–7th centuries and the solar coronal structure in the Dalton Minimum. Our team has also contributed to an invited review of sunspot number recalibration, which extensively covers recent developments in this field (Clette et al., 2023).

Simulation Study on the mechanism of magnetic helicity formation in solar active region

Solar active regions are formed when magnetic flux in the solar interior rises to the solar surface, often causing flare explosions. This is attributed to the sudden release of energy associated with the twisting of the magnetic field (magnetic helicity) accumulated in active regions. However, the formation mechanism of magnetic helicity in active regions has not been completely elucidated. The research team of the Integrated Studies Division, in collaboration with Lockheed Martin Solar Astrophysics Laboratory, Chiba University, and ISAS/JAXA, has systematically computed the process of magnetic flux rising inside complex convection in the solar interior using the supercomputer "Fugaku," and found that the downward flow in the solar interior plays an important role in the formation of large magnetic helicity. This is because the downward flow causes collisions between positive and negative magnetic poles on the solar surface. Then, the magnetic poles can rotate and form a large magnetic helicity in the active region because the magnetic helicity is converted from the twist of magnetic field lines to the writhe of the flux tube. They also found that even when a non-twisting magnetic flux tube emerges on the solar surface, magnetic helicity can form enough to generate small-to medium-sized flares due to the pair production of positive and negative magnetic helicity as the magnetic poles collide (Toriumi et al., submitted to *Sci. Rep*.).

New database of “AIA Active Region Patches”

Dr. KD Leka, CICR Designated Professor (cross-appointment) with colleagues at NorthWest Research (Boulder, Colorado, USA) established a new database of “AIA Active Region Patches” which extract time-series coronal and chromospheric E/UV images from AIA on the Solar Dynamics Observatory over 8 years (over 256,000 images). The database is curated for DEM inversions and readily applicable for Machine Learning and other large-sample cycle-long solar science (Dissauer et al 2023, *Astrophysical J*., 942, 83; 10.3847/1538-4357/ac9c06). Using this database, the team constructed active-region summarizing parameters that characterized the solar corona and chromosphere (including high-frequency dynamics and longer-term evolution) for the full sample. These publicly available parameters were then used with NonParametric Discriminant Analysis to ask “are flare-ready regions distinguishable by their coronal and chromospheric behaviors?” The answer is “yes” at a level similar to how well we can answer this question already using photospheric magnetic field data (e.g., True Skill Statistics in the 0.68–0.82 range, depending on event definition; Leka et al 2023, *Astrophysical J*., 942, 84; 10.3847/1538-4357/ac9c04). Thus, future research efforts (including Machine Learning efforts using these new flare-related parameters) may combine the coronal dynamics information with photospheric magnetic field data to improve forecasting for solar flares.

Examining global 3-d MHD simulations of thermal convection in solar like-stars from asteroseismic perspectives

Recent asteroseismic evaluations have revealed that some solar-like stars exhibit latitudinal differential rotation, the degree of which is much stronger than that of the Sun, suggesting a variety of dynamic mechanisms. In this study, we compared internal rotation profiles with those obtained based on global 3-d MHD simulations of thermal convection in solar-like stars. We adopted the numerical regime established by Hotta and Kusano (2021) (HK21 regime). No significant inconsistency was found between observations and theory (in the HK regime). However, observational uncertainties are large for slow rotators; thus, the comparison is inconclusive for slowly rotating solar-like stars. A larger number of asteroseismic studies on the internal rotation of solar-like stars is desirable.

First-principles simulation of solar wind using the Fugaku Supercomputer

Turbulent plasma flows and dynamo actions within the solar interior have long been regarded as direct energetic sources of solar wind acceleration. However, owing to significant differences in spatiotemporal scales, addressing this issue without relying on empirical assumptions has been challenging. For the first time, we successfully simulated solar winds with minimal empirical assumptions by utilizing large-scale numerical simulations on RIKEN’s Fugaku supercomputer. The realized solar wind is consistent with diverse observational constraints from the photosphere and corona to solar wind, suggesting that our simulation captures some aspects of the real solar wind acceleration process. Detailed evaluation revealed that magnetic reconnection is quantitatively significant in the energy transport process, which has primarily been attributed to Alfvén waves.

Development of higher-order FDTD method

A new explicit and non-dissipative finite-difference time-domain (FDTD) method in two and three dimensions is proposed for the Courant condition relaxation. Third-degree spatial difference terms with second- and fourth-order accuracies were incorporated with coefficients to the time-development equations of the FDTD (2,4). The optimal coefficients are obtained by a brute-force search of the dispersion relations, which reduces the phase velocity errors but also satisfies the numerical stabilities. The new method is stable with large Courant numbers, whereas the conventional FDTD methods are unstable. The new method also has smaller numerical errors in the phase velocity than the conventional FDTD methods with small Courant number (10.1109/TAP.2023.3234097).

Fit of atomic oxygen ion-neutral collision cross section at ionospheric temperatures

Atomic oxygen and its ions are the major species in the ionosphere of Earth, Venus, and Mars. Collisions between them control the ionosphere structure and are expressed by collision cross-sections or frequency models. Recently, it has been suggested that textbook high-energy models should be replaced with wide energy models. However, there are three wide-energy-type models, and it is obscure which of these is the most appropriate for ionospheric studies. The valid temperature range of their fits was obscure, although it was probably between 300 and 2000 K, which is typically sufficient only for the quiet-time F-region ionosphere of the Earth. This study elucidates the differences among the three models and proposes a new fit by including the curved trajectory effect in the fitting basis function. Consequently, the valid temperature range was improved to 75–9000 K, which is sufficient for the entire ionospheres of Earth, Venus, and Mars, including rare occasions.

Spatial relation of enhanced electric field and particle boundaries associated with SAPS

Fast westward flow, called subsutural polarization streams (SAPS), is often observed at subauroral latitudes on the night side during magnetically disturbed times. We analyzed Arase satellite and SuperDARN radar data to investigate how the inner boundary of the SAPS electric field corresponds to those of the ring current and plasma sheet. The results demonstrated that the inner boundary of the ion ring current appears to often extend further inward from SAPS. It is interpreted that previously injected ions and fresh ring current ions coexist in the inner magnetosphere and only the latter contributes to the SAPS formation.

Computer simulation on pulsating aurora by non-linear wave particle interaction

Pulsating auroras are caused by the intermittent precipitation of electrons into the thermosphere, which are scattered in the pitch angle by wave-particle interactions caused by chorus waves. The nonlinear interaction between chorus waves and electrons often results in a complex relationship between the intensity of the waves, the flux of incoming electrons, and the intensity of auroral emissions. In this study, we employed a wave-particle interaction code based on test particle computations and an auroral emission code to investigate the variation of auroral emissions with the intensity of chorus waves. Our findings indicate that when phase trapping dominates, the intensity of the auroral emission decreases and the number of electrons causing the aurora is suppressed. Conversely, in the case of dislocations, the number of electrons causing the aurora, including optical emission, significantly increased. These results suggest that the auroral luminosity intensity is not simply related to the chorus waves intensity but undergoes complex variations owing to nonlinear wave-particle interactions. The results of this study are expected to contribute substantially to the understanding of the nature of pulsating auroras that exhibit a variety of responses to plasma waves.

Studies of energetic ion behaviors and structured EMIC waves using the Arase satellite observations

We performed two statistical studies using the Arase satellite observations from March 2017 to December 2021: 1) energetic ions (H^+, He^+, and O^+) depending on geomagnetic conditions and 2) the characteristics of structured electromagnetic ion cyclotron (EMIC) waves in the inner magnetosphere. In the first study, we found four distinct ion populations within different energy ranges: (1) plasmaspheric ($E<30$ eV) ions at $L<5$, (2) warm plasma cloak at energies of 10s eV–several keV, (3) the ring current population (E = 1 keV–10s keV) with nose structures, (4) high-energy ring current particles ($E>30$ keV) with symmetric distributions in MLT, and these populations exhibited different behaviors as Kp increases. In this study, we discussed the underlying physical dynamics and the possible origins of the different populations and compare the observational results with a model calculation using simple electric and magnetic fields. In the second study, we found the preferred conditions of structured EMIC waves. They are predominantly observed on the dayside of the magnetosphere at MLAT > 20 deg with stronger curvature forces than other types of EMIC waves. These waves were observed in an increase of solar wind dynamic pressure before the EMIC wave onset. We suggest that increasing solar wind dynamic pressure causes inhomogeneity of the dayside magnetic field, driving the preferred conditions to trigger non-linear wave growth. This leads to a more frequent occurrence of structured EMIC waves at higher latitudes on the dayside of the magnetosphere.

Global modeling and observations of proton precipitation in the sub-auroral latitudes during the 27 May 2017 storm and its association to EMIC waves

Recent studies have demonstrated that ion precipitation induced by EMIC waves can contribute significantly to the total energy flux deposited into the ionosphere and severely affect the magnetosphere-ionosphere coupling. During the geomagnetic storm of May 27–28, 2017, the DMSP and NOAA METOP satellites observed enhanced proton precipitation in the dusk-midnight sector during the major phase of the storm. The ARASE and RBSP-A satellites observed the typical signatures of EMIC waves in the inner magnetosphere. To comprehend the evolution of proton precipitation into the ionosphere, its correspondence to the time and location of wave excitation, and its relation to the source and distribution of proton temperature anisotropy, we performed two BATSRUS+RAMSCBE model simulations with and without EMIC waves. In regions where the Arase/RBSP-A satellite measurements recorded EMIC wave activity, an increase in the simulated growth rates of H- and He-band EMIC waves was observed. The H- and He-band EMIC waves were excited within regions of strong proton temperature anisotropy in the vicinity of the plasma pause, which is consistent with previous observations. The simulated precipitation fluxes were found to be in good agreement with DMSP and NOAA MetOP satellite observations. These results suggest that the RAM-SCBE model can capture EMIC wave activity and qualitatively reproduce precipitating fluxes in the pre-midnight sector. Our results demonstrate that the EMIC wave scattering of ring current ions gave rise to proton precipitation in the pre-midnight sector at subauroral latitudes during the major phase of the May 27, 2017, storm.

Plasma pressure distribution of ions and electrons in the inner magnetosphere during CIR driven storms observed during Arase era

The storm-time ring current is driven by the plasma pressure in the inner magnetosphere. The plasma pressure is predominantly contributed by protons in the energy range of a few keV to a few hundred keV. O+ contribution increases during the geomagnetically active period. However, the contribution of electrons to the ring current has not been well studied. Using Arase observations during 26 CIR-driven geomagnetic storms (Sym-H < −40 nT), we investigated the ring current pressure development of ions (H^+, He^+, O^+) and electrons during the pre-storm, main, early recovery, and late recovery phases with an L-shell and magnetic local time (MLT). During the main and early recovery phases of the storm, the ion pressure was asymmetric in the inner magnetosphere, which led to a strong partial-ring current. H^+ with an energy of approximately 55 keV contributed more to the ring current pressure during the main phase. O^+ with an energy of approximately 10–20 keV, contributed significantly to the main and early recovery phases. Electrons with energies of < 50 keV contributed to the ring current pressure during the main/early recovery phase of the storm. Overall, the electron contribution to the total ring current was approximately 11% to the total ring current during the main and early recovery phases. However, the electron contribution was significant at approximately 22% in the 03–09 MLT sector during the main and early recovery phases. These results indicate the important role of electrons in the ring current build-up. Therefore, the contribution of electrons to the ring current should be carefully studied.