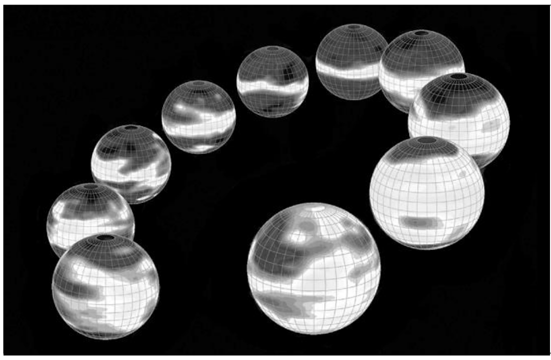
Division for Heliospheric Research



- Solar wind and heliosphere
- Interplanetary scintillation (IPS)
- Coronal mass ejection (CME)
- Long-term variation of the heliosphere
- Space weather forecast
- Radio astronomy
- Development of telescopes and instruments
- Pulsar

A supersonic (with a speed of 300–800 km/s) plasma flow, known as the solar wind, emanates from the Sun and permanently engulfs the Earth. While the magnetic field of the Earth acts as a barrier to protect the atmosphere from a direct interaction with the solar wind, a considerable fraction of its vast energy enters the near-surface layer via various processes. Thus, the solar wind acts as a carrier to transfer the Sun's energy to the Earth.

The solar wind varies dramatically with solar activity. In association with eruptive phenomena on the Sun's surface, a high-speed stream of the solar wind sometimes arrives at the Earth and generates intense disturbances in the geospace and the upper atmosphere. Space environmental conditions that significantly change with solar activity are known as "space weather," and are currently a topic of significant interest. An accurate understanding of the solar wind is required to make reliable predictions of space weather disturbances.

We have observed solar wind velocity and density irregularities for several decades using three large antennas to investigate unsolved important issues such as acceleration and propagation mechanisms of the solar wind, space weather forecasting, global structure of the heliosphere, and its variation. In addition, laboratory and fieldwork experiments were performed to improve the data quality and upgrade the instruments.

Main Activities in FY2022

Solar wind observations using the IPS system

Remote-sensing observations of solar wind have been performed since the 1980s using a multistation interplanetary scintillation (IPS) system. Tomographic evaluation of IPS observations enables accurate determination of the global distribution of solar wind speed and density fluctuations. IPS observations provide valuable information, particularly for high-latitude solar winds, wherein *in situ* observations are currently unavailable. Currently, IPS systems comprise three large antennas: Toyokawa, Fuji, and Kiso. The Toyokawa antenna (SWIFT) has the largest aperture and highest sensitivity among the three antennas and began daily observations in 2008. The Fuji and Kiso antennas were upgraded in 2013–2014 by installing new receivers, which significantly improved their sensitivities. These antennas are located in mountainous areas and are not used for observations during winter due to heavy snowfall. Hence, solar wind speed data from the three station observations were unavailable during winter. Instead, solar wind density fluctuations were derived from the Toyokawa IPS observations, which were measured throughout the year. The IPS data were made available to the public in real time via an FTP server and used for diverse international collaborations. In this FY, three-station IPS observations were initiated in early April using the Toyokawa, Fuji, and Kiso antennas. The IPS observations at Fuji stopped owing to a failure of the antenna driving shaft on July 28, and restarted after restoration work on August 12. However, the IPS observations at Kiso stopped due to a failure of the antenna driving system on September 14. Although several attempts were made to fix the Kiso antenna issue, we could not successfully restore the antenna and deferred restarting the IPS observations at Kiso.

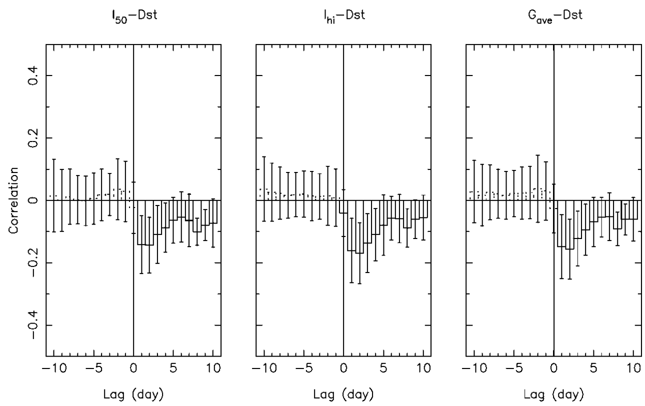
International collaboration for space weather forecast and heliospheric sciences

Since 1996, we have performed collaborative research with Dr. B. V. Jackson and his colleagues at the University of California, San Diego (UCSD) on the three-dimensional reconstruction of the time-varying heliosphere using tomographic analysis of IPS observations. A time-dependent tomography (TDT) program was developed for this collaborative study. Furthermore, a combined analysis system using IPS observations and an ENLIL solar wind model was developed to improve space-weather forecasting. These programs are now available on the NASA Community Coordinated Modeling Center web server and run in real time at the Korean Space Weather Center (KSWC) to predict solar winds reaching Earth. Furthermore, the IPS-driven ENLIL model installation is under consideration by the UK Met Office.

With growing awareness of the utility of IPS observations for space weather forecasting, an increasing number of IPS observations have been performed globally. In Japan, Russia, and India, where IPS observations have been performed for a long time, a new dedicated antenna for IPS observations was constructed in Mexico, and IPS observations using low-frequency large radio array systems, such as the low-frequency array (LoFAR, EU), were performed on a campaign basis. In this FY, the UCSD TDT evaluation was compared with the dispersion measures (DMs) of the pulsars obtained from LoFAR observations. DM represents the integrated plasma density along the line of sight of the pulsar. The observed DMs exhibited variations in the solar elongation angles. The variations in the observed DMs were consistent with the integrated plasma density of the solar wind derived from the TDT analysis. Furthermore, we collaborated with the research group of Dr. Bzowski (Poland) in this FY on the global modeling of solar wind distribution using ISEE IPS observations. Bzowski et al. studied the charge exchange process between solar wind plasma and interstellar neutrals and required a model that determines solar wind global distribution, evolving with solar activity is essential in their study. The model developed in this collaboration enabled reliable and continuous determination of the global distribution of solar wind and interpolation of gaps in IPS observations during winter. This result will contribute to a better understanding of Interstellar Boundary Explorer (IBEX) observations.

Study of solar wind disturbances using g-value data

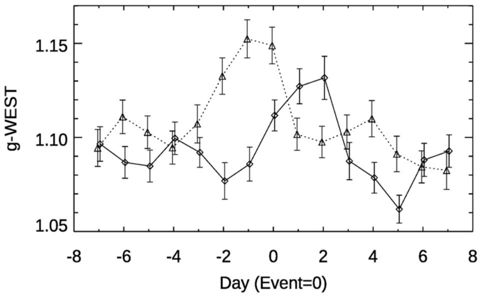
The space environment (space weather) near Earth drastically changes when the CME or stream interaction region (SIR) arrives, and its influence affects radio communications and electric power facilities on the ground. Therefore, early solar wind disturbances detection is essential. IPS observations, which are remote sensing techniques, may have the potential to detect solar wind disturbances earlier than *in situ* measurements at the L1 point. To apply IPS observations to space weather forecasts, we examined the variations in IPS data associated with the arrival of solar wind disturbances in this FY. We evaluated g-value data obtained from ISEE IPS observations during Solar Cycles 23 (SC23) and 24 (SC24). The g-value represents the relative change in the integrated level of solar wind density fluctuations along the line of sight. The g-value is equal to unity for quiet solar winds and increases above one when solar wind disturbances intersect the line of sight. We computed the IPS indices from the g-value on daily basis and compared them with the solar wind density and speed data observed *in situ* near Earth. We found weak but significant positive correlations between the IPS indices and solar wind density/speed. The correlation coefficients peaks occurred at a time delay of zero days for the IPS indices for density and at a time delay of 1–2 days for speed. This suggests that enhancements in the IPS indices represent the compression region at the IP shock front. We also compared the IPS indices with geomagnetic Dst indices and found weak but significant negative correlations with the IPS indices at a time delay of 1–2 days to the IPS indices. Additionally, we determined the annual variation in the occurrence rate of solar wind



Correlations between the IPS indices (I_{50}, I_{hi}, G_{ave}).

disturbances from the IPS indices and found that the occurrence rates tended to increase at the solar maximum and minimum, unlike the sunspot number. This can be elucidated by the combined effects of CME and SIR. The occurrence rates at the solar maximum for SC24 were lower than those for SC23, which is consistent with the solar activity weakening in SC24. Thus, these results demonstrate that the g-values are useful for detecting solar wind disturbances.

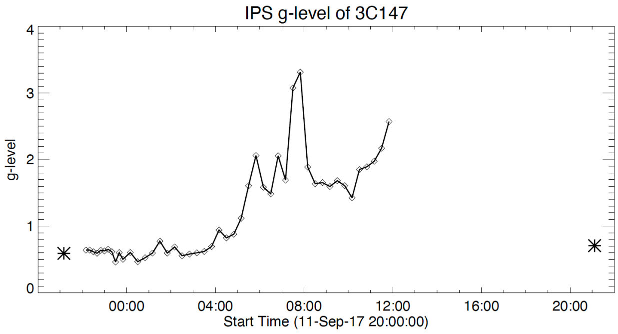
Additionally, the daily changes in the g-values were computed separately or on the East and West sides of the Sun, and the typical g-value profiles for ICME and SIR were obtained by Superposed Epoch Analysis. The results demonstrated a clear difference between the ICME and SIR profiles in the daily variation of the solar western g-value. That is, ICME (dotted line) had a maximum between -1 and 0 days, whereas SIR (solid line) had a maximum between +1 and +2 days.



Typical g-profiles of ICMEs and SIRs in SC23

Three-dimensional reconstruction of CMEs using MHD simulation with IPS data observed from radio sites ISEE and LOFAR

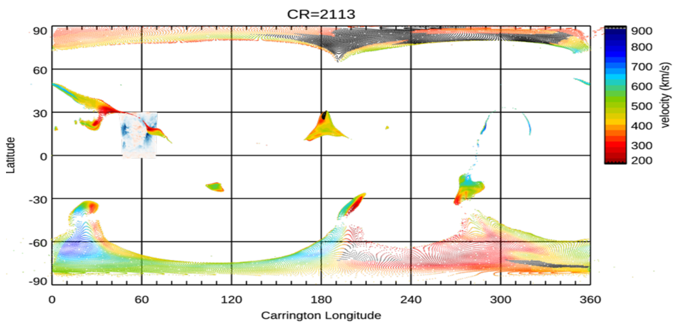
The IPS is a useful tool for detecting the interplanetary space of a CME. In this study, we demonstrated an MHD simulation that included IPS data from multiple ground-based stations to improve the 3D reconstruction of CME modelling. The CMEs, which occurred on 09–10, 2017, were observed from September 10 to 12, 2017, using the Low-Frequency (LOFAR) and IPS array of the Institute for Space-Earth Environmental Research (ISEE), Nagoya University, as they tracked through the inner heliosphere. We simulated CME propagation using a global MHD simulation called SUSANOO-CME. We found that the MHD simulation that best fitted both LOFAR and ISEE data provided a better CMEs 3D reconstruction and a forecast of their arrival at Earth than the measurements when these simulations were fit from the ISEE site alone. More IPS data observed from multiple stations at different local times in this study can help reconstruct the global structure of the CME, thus improving and evaluating CME modelling.



Time validation of the IPS g-level of a radio source 3C147 by ISEE (*) and LOFAR (◇)

Study on the relationship between plasma upflow and slow solar wind by Hinode/EIS and IPS observations

We studied the plasma upflows at both active region ends, which have been suggested to be the source of slow solar wind due to their elemental composition similarity to slow solar wind. We studied the relationship between the plasma upflow and open magnetic field lines by comparing the position of the upflow observed using an Extreme Ultraviolet Imaging Spectrometer (EIS) on the Hinode satellite and the photospheric magnetic field computed using the Potential-Field-Source-Surface (PFSS) model. The relationship between the plasma upflow and the open magnetic field lines was studied using the PFSS

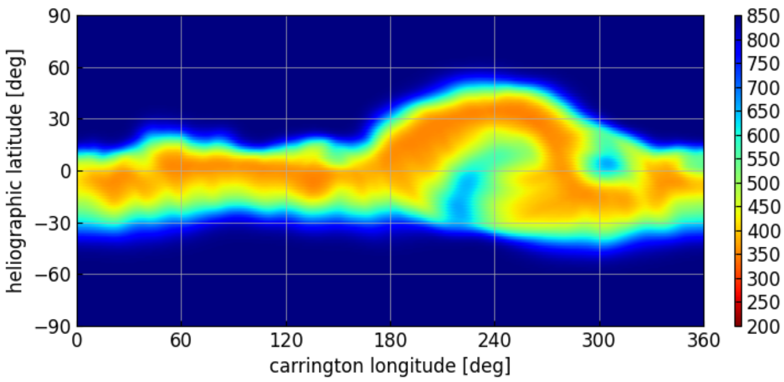


The EIS data (rectangular area around 60° longitude) and the footprint at $R=1.01R_0$ (solar radius) of the open magnetic field determined by the PFSS were superimposed. The color represents the solar wind velocity to which the open magnetic field lines are connected. In this figure, the upflow is connected to the open magnetic field lines. A color figure is included in the PDF version.

model. Furthermore, using the IPS data, the solar wind velocity connected to the open magnetic field lines were evaluated. It was found that some upflows were magnetically connected to slow solar winds, whereas some upflows were trapped in a closed magnetic field. EIS data evaluation demonstrated that, in the upflow region connected to the closed magnetic field, the excess broadening of the spectral linewidth, called the nonthermal velocity, was larger than that in the open magnetic field region.

Optimization of DCHB model of the solar wind using IPS observation

However, the sources of solar wind and its acceleration mechanisms are not yet completely understood. Several models have been proposed to empirically link the topology of the solar coronal magnetic field to solar wind velocity. We examined a solar wind model, the Distance of Coronal Hole Boundary (DCHB) model, using IPS data. The parameters of the DHCB model were optimized for the solar wind velocity data from the IPS observations, and the reproduced solar wind distribution was assessed. We computed the (PCC) between the solar wind speed reproduced by the DCHB model and that derived from the IPS observation and determined the parameters that maximize the PCC as the optimal parameters. Unlike *in-situ* observations, IPS observations enable the determination of the global distribution of solar wind speed. Therefore, the DCHB model can be validated more effectively using the IPS observations. In this evaluation, we also used the Potential Field Source Surface (PFSS) model to estimate the coronal magnetic field and magnetograms structure from the Air Force Data Assimilative Photospheric Flux Transport (ADAPT) as its lower boundary condition. Consequently, during the solar minimum, the PCC was as high as 0.81. This high correlation is mostly attributed to the excellent reproduction of the solar wind bimodal structure at the solar minimum by the DCHB model, and it is known that high- and low-speed winds dominate at high and low latitudes, respectively, at the solar minimum. It is also known that high-speed wind almost disappears at the solar maximum, and low-speed wind dominates at all latitudes.



Solar wind velocity map reproduced by the DCHB model

Next generation IPS observation system

We promoted a next-generation solar wind observation system to dramatically improve IPS observations at the Division for Heliospheric Research. In FY2021, a Grant-in-Aid for Scientific Research (A) was adopted, and the construction of a core array with a scale of 5% of the total for Fuji Station began. In FY2022, we developed a digital backend system that can digitize 64-channel signals with eight AD modules installed directly below the front end and synthesize up to eight beams in real time with an FPGA array connected by optical fibers. All digital devices were delivered by the end of March. Additionally, we designed an antenna system. We considered the dipole- and Yagi-type antenna systems and developed their prototypes.

We promoted the next generation IPS observation system to propose it to “Future Plan for Academic Advancement.” We received a hearing from the Earth and Planetary Science community at the JpGU 2022 union session. This project was also proposed in a booklet summarizing the plans of the astronomy and astrophysics community. The proposal was submitted to the future academic promotion plan as a part of the “Study of coupling processes in the solar-terrestrial system” project by merging with some ground-based future projects of the upper atmosphere community.