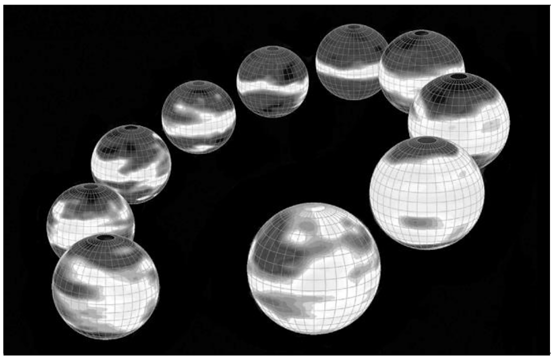
Division for Heliospheric Research



- 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 FY2021

Solar wind observations using the IPS system

We have been performing remote-sensing observations of the solar wind since the 1980s using a multi-station interplanetary scintillation (IPS) system. Tomographic analysis 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, where *in-situ* observations are currently unavailable. The IPS system currently consists of three large antennas in Toyokawa, Fuji, and Kiso. The Toyokawa antenna (called the Solar Wind Imaging Facility Telescope: SWIFT) has the largest aperture and highest sensitivity among the three antennas and started daily observations in 2008. The Fuji and Kiso antennas were upgraded in 2013–2014 by installing new receivers, which significantly improved their sensitivity. These two antennas are in mountainous areas and are not used for observations during winter owing to heavy snowfall. Hence, the solar wind speed data from three-station observations were unavailable during winter. Instead, the 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 various international collaborations. In this fiscal year, three-station IPS observations were conducted between early April and early December using Toyokawa, Fuji, and Kiso antennas. Observations with the Fuji antenna were frequently interrupted owing to failure of the driving system from late June to early August and late November to early December. In addition, the Sugadaira antenna, which had been out of order due to snow damage, was removed from this fiscal year.

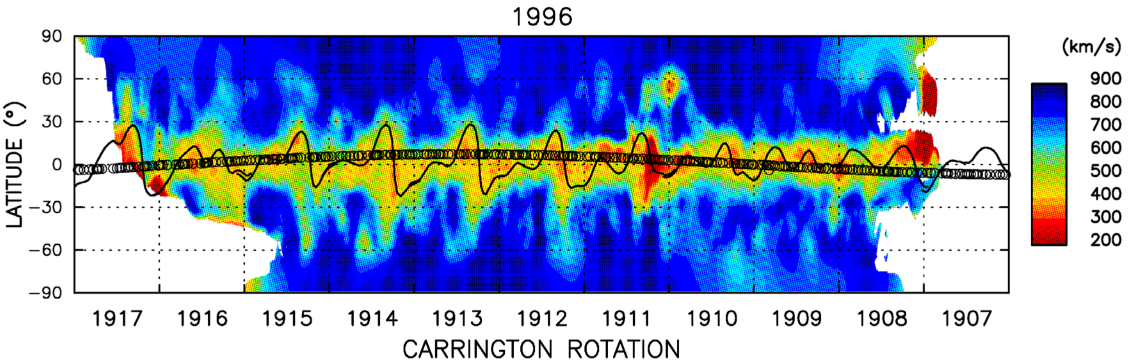
International collaboration for space weather forecast

We have performed collaborative research with Dr. B. V. Jackson and his colleagues at the University of California, San Diego (UCSD) since 1996 on the 3-dimensional reconstruction of the time-varying heliosphere using tomographic analysis of IPS observations. A time-dependent tomographic (TDT) program was developed through this collaborative study. Furthermore, a combined analysis system using IPS observations and the ENLIL solar wind model was developed to improve space weather forecasting through collaborations. These programs are now available on the NASA Community Coordinated Modeling Center web server and are running in real time at the Korean Space Weather Center (KSWC) to predict the solar wind reaching the Earth.

With growing awareness of the utility of IPS observations for space weather forecasting, an increasing number of IPS observations have been conducted globally. In Japan, Russia, and India, where IPS observations have been conducted 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 conducted on a campaign basis. In this fiscal year, the integrated analysis of IPS data from ISEE, LoFAR, and Russia was performed using the TDT program for three periods (Orbit 1–3) when the Parker Solar Probe approached the Sun. TDT analysis was compared with PSP in situ measurements and discrepancies between them were found in the solar wind speed and density. The cause for these discrepancies is currently under investigation and we will compare the IPS and PSP observations for the periods after Orbit 3.

Improvement of IPS tomography and long-term change in solar wind turbulence

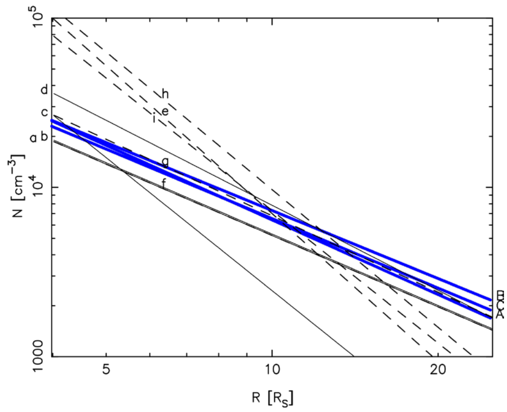
In performing the tomographic analysis of solar wind speeds obtained from IPS observations, information on the spatial distribution of density fluctuations (ΔN_e) along the line of sight is required. Previous studies have shown that the following relationship exists between ΔN_e and speed V: $\Delta N \propto V^{\alpha}$, $\alpha = -0.5$. The tomographic analysis with this relation yielded solar wind speeds that showed good agreement with *in situ* measurements (such as OMNI data and Ulysses observations) for Solar Cycle 23 (SC23). However, the comparison between IPS and *in situ* measurements for Solar Cycle 24 (SC24) revealed a systematic discrepancy between them; the speeds from the tomographic analysis were higher than those from *in situ* measurements by 50–100 km/s. We examined the possible causes for this discrepancy and found that it can be improved by changing the value of the index α. The optimal value for α to produce the best agreement between the tomographic analysis and *in situ* measurements was +0.5. According to a recent theoretical study, ΔN_e is a key parameter for controlling the efficiency of solar wind acceleration, and the results obtained from this study suggest that acceleration efficiency varies with the solar cycle. The solar wind speed data obtained in this study were used in collaboration with Dr. Bzowski (Poland) to develop a global model of solar wind density that covers a long period.



Synoptic map of solar wind speed derived from tomographic analysis of IPS observations for 1996. The solid line indicates the magnetic neutral line determined from magnetographic observations at the Wilcox Solar Observatory. Open circles indicate the locations of Earth, that is, where OMNI data were collected (Tokumaru et al., 2021).

Coronal density measurements using giant radio pulses of the Crab pulsar

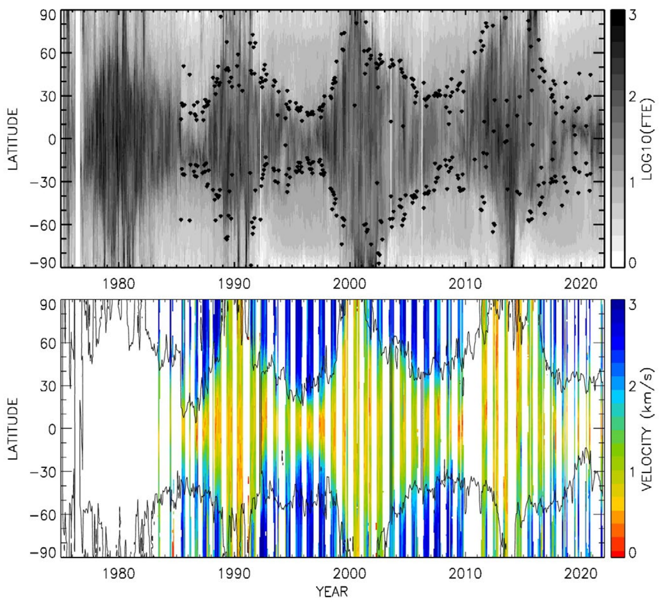
Crab pulsar observations have been carried out using the Toyokawa antenna since 2017 to examine the coronal plasma density. The radio waves from a pulsar are delayed upon arrival owing to the effect of plasma intervening between the source and observer. The line-of-sight integration of the plasma density (dispersion measure, DM) can be estimated by measuring this delay. The line of sight for the Crab pulsar approaches the Sun every June, up to a distance of five solar radii. If the DMs for the Crab pulsar are measured during the closest approach to the Sun, the coronal density can be estimated from the excess in the DM compared to those when the Crab pulsar is in opposition to the Sun. In addition, the Crab pulsar sporadically emits strong radio waves (giant radio pulses, GRPs), and the DMs can be accurately determined in a short time using GRPs. In this study, we analyzed the DM data collected in 2018 and 2019 (SC24/25 minimum) from Crab pulsar observations at Toyokawa to develop a model of coronal plasma density between 5 and 60 solar radii. The density model obtained in this study agreed with those in the low-activity periods of the past solar cycles within the margin of error. A significant drop in the solar wind density was reported for the previous (SC23/24) minimum. The results of this study suggest the recovery of the solar wind density at this minimum to the level of past minima.



Coronal density models obtained from Crab pulsar observations at Toyokawa for 2018 and 2019 (Thick lines A-C). The density models obtained in the low and high activity periods of the past solar cycles are indicated by thin solid (a-d) and bashed (e-i) lines, respectively (Tokumaru et al., 2022).

Reconstruction of the global structure of the solar wind during 1975–1985

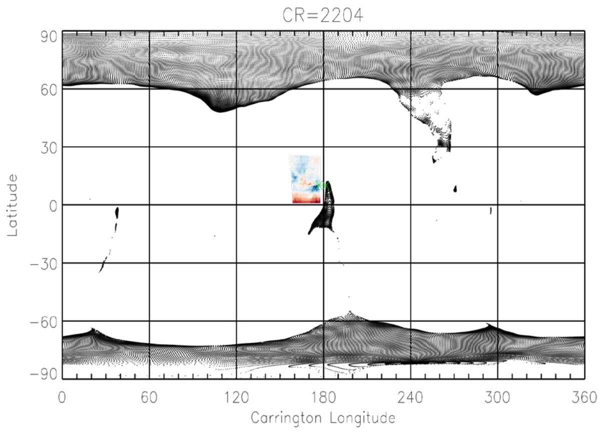
It is well known that solar winds consist of low-latitude slow winds (<450 km/s) and high-latitude fast winds (~800 km/s) except during the maximum. Because the boundary latitude between fast and slow solar winds is highly dependent on the solar activity cycle, it is expected to be used as a foothold for understanding the solar cycle in solar wind. We previously clarified the distribution of coronal holes, which are the origin of the solar wind, and revealed that their distribution resembles a sunspot butterfly diagram. In 2021, we compared IPS observations with the magnetic flux tube expansion factor (FTE) calculated from potential field source surface (PFSS) analysis. First, we derived the average of FTEs at the boundary latitudes in each Carrington rotation, which was found to be log10(FTE)=0.97±0.56 (see upper panel). Next, we plotted the latitudes at log10(FTE)=0.97 on the solar wind structure (see the lower panel). As a result, we found that latitudes at log10(FTE)=0.97 generally coincided with the velocity boundary latitudes obtained from the IPS observations. The contour can be extrapolated to the past, which has allowed us to estimate the global structure of solar wind since 1975.



Upper panel: FTE distribution on the source surface (2.5Rs) and latitudinal boundary (black dots) obtained from IPS observations. Lower panel: IPS observations and contour of log10(FTE)=0.97 (black curves).

Investigation of plasma upflow and slow solar wind using Hinode/EIS and IPS observations

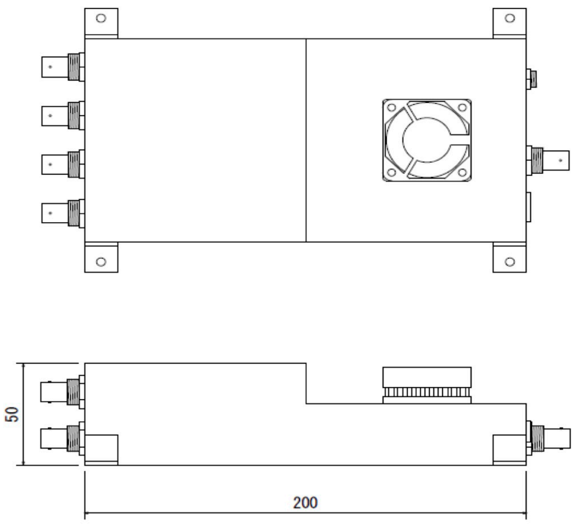
We studied plasma upflow in the solar active region. Plasma upflow was detected using an extreme ultraviolet imaging spectrometer (EIS) onboard the Hinode satellite. The elemental composition of the plasma upflow was similar to that of slow solar wind, suggesting that it was the source of the slow solar wind. We studied the relationship between plasma upflow and the open magnetic field by comparing EIS observations with photospheric magnetic fields calculated using the potential field source surface (PFSS) model. As a result, it was found that plasma upflow can be classified into two patterns: one is located near an open magnetic field and the other is located near an open magnetic field. Furthermore, by comparing the PFSS model with the IPS data, we found a correlation between the active region where the upflow exists and the location of the slow solar wind.



The EIS observation data (boxed area in the center) and the footprint in the photosphere of the open magnetic field lines determined by PFSS are superimposed. It can be seen that the open magnetic field lines exist near the plasma upflow.

Next generation IPS observation system

We promoted the next-generation solar wind observation system to dramatically improve IPS observations at the Division for Heliospheric Research. In FY2021, we decided to submit a proposal to Master Plan 2023. We received hearings of the proposal as a middle-scale plan (B) from the astronomy and astrophysics community and as a middle-scale plan from the Earth and planetary science community. Although the Master Plan itself covers larger-scale plans than our plan, the hearings this fiscal year also include milled scale plans of billions-yen scale to look into the future of the research fields, which made it possible for our plan to be proposed as well. Although Master Plan 2023 itself was not summarized, it made great progress in advertising our plan to each community. In addition, we applied for Specially Promoted Research of the Grants-in-Aid for Scientific Research (KAKENHI) and submitted proposals for the budget requests of ISEE. In FY2021, a Grant-in-Aid for Scientific Research (A) was adopted and construction of a core array that has a scale of 5% of the total for the Fuji station was started. We completed the system design of 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. Unfortunately, delivery of the system was postponed until FY2022 due to the worldwide shortage of semiconductors. However, there has been significant progress in completing the system design of the backend.



AD module of the next generation solar wind observation system.