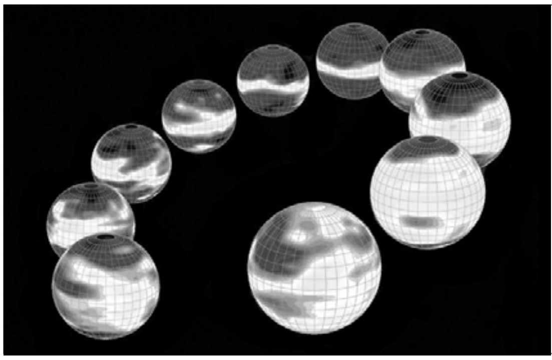
Division for Heliospheric Research



- Solar wind
- Coronal mass ejection
- Interplanetary scintillation
- Global heliospheric structure
- 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 geospace and the upper atmosphere. Space environment conditions that significantly change with the solar activity are known as "space weather," and are currently a topic of significant interest. An accurate understanding of the solar wind is needed 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 are performed for improving data quality and upgrading the instruments.

Main Activities in FY2018

Solar wind observations using the IPS system

We have been performing remote-sensing observations of the solar wind since the 1980s using the multi-station Interplanetary Scintillation (IPS) system. Tomographic analysis of IPS observations enables accurate determination of the global distribution of the solar wind speed and density fluctuations. IPS observations provide valuable information, particularly for high-latitude solar wind, where in situ observations are currently unavailable. The IPS system currently consists of three large antennas at Toyokawa, Fuji, and Kiso. The Toyokawa antenna (called the Solar Wind Imaging Facility Telescope, SWIFT) has the largest aperture and highest sensitivity among our three antennas and started daily observations in 2008. The Fuji and Kiso antennas were upgraded in 2013–2014 by installing new low-noise amplifiers (LNAs), which led to a great improvement in their sensitivity. These two antennas are located in mountainous areas and are not used for observations during winter due to heavy snowfall. Solar wind density fluctuations were derived from IPS observations at Toyokawa and measured throughout the year. The IPS data were made available to the public in real time via an ftp server, and were used for various international collaborations, as described below. In this FY, IPS observations were interrupted as the Fuji antenna was seriously damaged by two big typhoons that occurred in September. The designation of the radio astronomical facility for the ISEE IPS system expired in December. We submitted its renewal application to the Ministry of Internal Affairs and Communications, and obtained its extension for 10 years (up to 2028 December).

International collaboration for space weather forecast

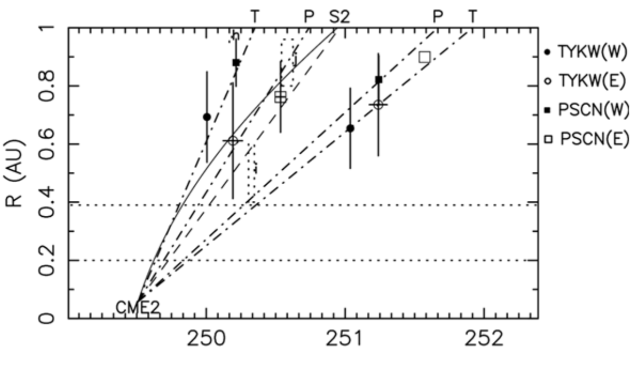
We performed collaborative research with Dr. B. V. Jackson and his colleagues at the University of California, San Diego (UCSD), on 3D reconstruction of the time-varying heliosphere using tomographic analysis of IPS observations over a long period. The time-dependent tomography program was developed through this collaborative research, and this program is now available on the web server of the NASA Community Coordinated Modeling Center (CCMC), and is running in real time at the Korean Space Weather Center (KSWC) to predict the solar wind at the Earth. The ISEE signed an agreement on research exchange and cooperation with KSWC in 2012 and renewed this in 2016. In this FY, we presented an invited talk on IPS observations of ISEE in the 8th Space Weather Conference (at Seoul, Korea) organized by KSWC. Three persons involved in KSWC visited ISEE in December and discussed with us the analysis method of IPS observations.

World-wide IPS Stations (WIPSS) Project

With the growing awareness of the utility of IPS observations for space weather forecasting, an increasing number of IPS observations has been conducted globally. Besides Japan, Russia, and India, where IPS observations have been conducted for a long time, new dedicated antennas for IPS observations have been constructed in Mexico and Korea and IPS observations using low-frequency large radio array systems, such as the low-frequency array (LoFAR) and the Murchison widefield array (MWA), have been conducted on a campaign basis. A construction project of a large-aperture antenna dedicated for IPS observations is in progress in China. An integrated analysis using IPS data from these stations enables higher-resolution 3D reconstructions of the solar wind rapidly varying with solar activity. Establishment of WIPSS was proposed at the IPS workshop held at Morelia, Mexico, in 2015. In this FY, we joined the IPS workshop held at Tongliao, China, in October. We also joined the MWA project meeting held at Nagoya University in December to present an invited talk on our IPS studies and discussed collaborations with Dr. John Morgan from the MWA project after that meeting. A party from the Chinese IPS group (four persons including Dr. Yihua Yan) visited ISEE in January and held a discussion on IPS observations and a field trip to the Toyokawa IPS antenna.

Coordinated observations of interplanetary disturbances in Japan and Russia

Traveling interplanetary disturbances associated with the halo coronal mass ejection (CME) events on September 4 and 6, 2017, were clearly detected in IPS observations at ISEE, Japan, and PRAO, Russia. The disturbances detected by IPS are ascribed to high-density plasmas associated with the shocks driven by those CMEs. As two observation stations are located at widely separated longitudes, a combined analysis of these IPS data enables high cadence tracking of the shock propagation. In this study, we derived g-values from PRAO IPS observations to compare with those derived from ISEE IPS observations. The g-value represents relative variation of solar wind density fluctuations along the line of sight (LOS), which becomes greater than 1 when a dense plasma intersects the LOS. We extracted data with $g > 1.5$ from ISEE and PRAO g-values and plotted the locations (distances from the Sun) of the LOS as a function of time to investigate the propagation process of the shocks driven by two halo CMEs between the Sun and the Earth orbit. The shock speeds inferred from the time-distance plots were much faster than those inferred

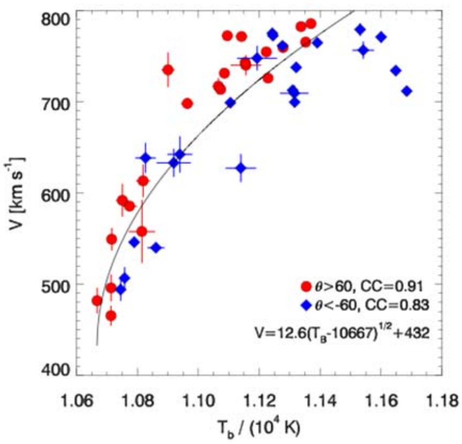


Propagation profile of the shock derived from IPS observations in Japan (Toyokawa, TYKW) and Russia (Pushchino, PSCN) for the September 6, 2017, halo CME event.

from the arrival time of the shocks at the Earth, which suggested that CMEs launched from the corona with a fast initial speed were rapidly decelerated in the interplanetary space. The IPS data also revealed the longitude dependence of the shock speed. IP disturbances propagating with a speed slower than the shock speed arriving at the Earth were observed for the September 9 CME event. No significant difference in the propagation speed was found between the east and west of these slow disturbances, suggesting that the disturbances expanded isotropically. While the origin of the slow disturbances remains an unsettled question, they may be ascribed to a wing portion of the shock.

Relationship between solar polar brightening and solar wind velocity

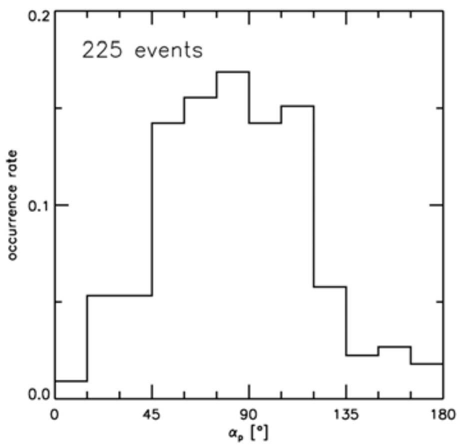
Solar polar brightening (PB) is an excess of brightness temperature (T_b) from a quiet disk level in the polar region, which is observed at frequencies between microwave and millimetric wavelengths. In this study, we compared the long-term variation (1992–2017) in PB observed with the Nobeyama Radioheliograph and polar V observed with interplanetary scintillation observations at the Institute for Space–Earth Environmental Research. By comparing V and T_b, we found good correlation coefficients (CCs) in the polar regions, CC = 0.91 (0.83) for the northern (southern) polar region. We derived an empirical formula of the V–T_b relationship as $V = 12.6(Tb–10{,}667)^{(1/2)}+432$, and then, analyzed the long-term variation of the PB and its relation with the area of the polar coronal hole (A). As a result, we found that the PB matches the probability distribution of the predicted coronal hole and that the CC between T_b and A is remarkably high (CC = 0.97). This result indicates that the PB is strongly coupled to the size of the polar coronal hole. Therefore, a reasonable correlation of V–T_b is explained by V–A. In addition, by considering the anti-correlation between A and f found in a previous study, we suggest that the V–T_b relationship is another expression of the Wang–Sheeley relationship in polar regions.



Relationships between V and T_b. Circle and diamond represent the data for north and south polar regions, respectively. Error bar represents one-sigma level.

Comparison of cylindrical interplanetary flux rope model fittings with different boundary pitch angle treatments

Interplanetary flux ropes (IFRs) are magnetic structures expelled from the Sun into interplanetary space. The magnetic field structure of an IFR comprises helical field lines around its axis. One of the most widely used methods for estimating this structure is the fitting of the Lundquist model. We evaluated two Lundquist model fitting methods by applying them to the magnetic obstacle events observed with the Wind and STEREO spacecraft and by comparing the results. In one method, the pitch angle of the magnetic field at the IFR boundary with respect to the axial direction is assumed to be 90°, and in the other method, this restriction is relaxed, and the pitch angle is handled as a free parameter α_p (hereinafter conventional and generalized methods, respectively). We found that the axis direction and magnetic flux of the IFR were significantly different. We also found that the statistical distribution of α_p, which was estimated using the generalized method, implies that a highly

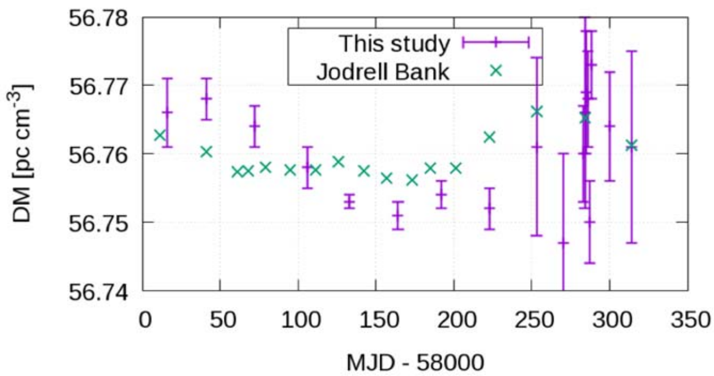


Histograms of pitch angle, α_p, as determined by the generalized method.

twisted magnetic field line surrounds the IFR surface for most of the events. These results prove that it is better to use the generalized method than the conventional method for solving the axis direction, magnetic flux, or pitch angle of the flux rope, which would lead to a more accurate derivation of the IFR properties.

Estimation of solar coronal density using the Crab pulsar

In recent years, a decrease in solar wind density due to declining solar activity has been highlighted from IPS and spacecraft observations. The coronal observations, which provide the source of the solar wind, are important for investigating the solar activity. One method for estimating the coronal density is to observe the dispersion measure (DM) of radio pulses radiated by a pulsar. DM is a parameter that represents the frequency dispersion observed in the pulsar signal, as well as the integrated electron density along the LOS. By taking the difference between the DMs when the LOS of the pulsar is located close to and far from the Sun, the (integrated) coronal density can be determined. We investigated the coronal density using the DM of the Crab pulsar. The LOS of the Crab approaches the Sun in mid-June, to as close as five solar radii over the South Pole. The Crab also emits exceptionally bright pulses, called giant pulses, which enable rapid DM estimation. The coronal density obtained from our observation was roughly in agreement with the value seen in the past at the solar activity minimum, which is the current solar activity. However, the error of the obtained value was large and no significant change from the value obtained in the past solar activity cycle could be confirmed. We will continue this observation for a higher accuracy of coronal density estimation.



Daily variations of DMs from the Crab pulsar observed by ISEE (-) and Jodrell Bank observatory (X).

Coronal mass ejection arrival time forecasting system using IPS observations

CMEs cause disturbances in Earth’s environment when they arrive at the Earth. However, the prediction of the arrival of CMEs remains a challenge. We developed an IPS estimation system based on a global magnetohydrodynamic (MHD) simulation of the inner heliosphere to predict the arrival time of CMEs, through a collaboration study with NICT, which has a Japanese space weather forecasting center. In this system, the initial speed of the CME is roughly derived from white-light coronagraph observations. Then, its propagation is calculated by a global MHD simulation. The IPS response is estimated by the three-dimensional density distribution of the inner heliosphere derived from the MHD simulation. The simulated IPS response is compared with the actual IPS observations performed by ISEE, and a good agreement is shown between them. We demonstrated how the simulation system works using a halo CME event generated by an X9.3 flare observed on September 5, 2017. We found that the CME simulation that best estimates the IPS observation can more accurately predict the time of arrival of the CME at the Earth. These results suggest that the accuracy of the CME arrival time can be improved if our current MHD simulations include IPS data. This system has been included in the real-time forecasting system in NICT.