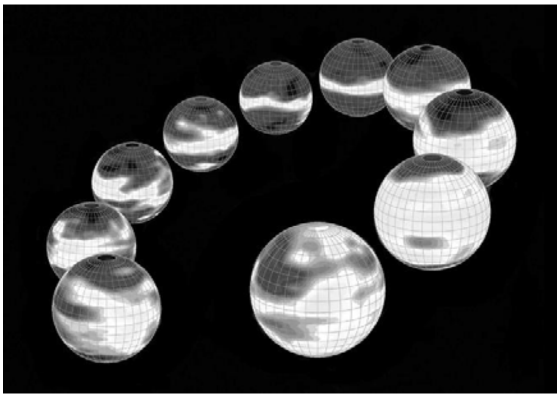
9-1. Research Divisions
Division for Heliospheric Research



Research topics and keywords

- Solar wind
- CME
- Radio astronomy
- Interplanetary scintillation
- Global heliospheric structure
- Space weather forecast
- Development of instruments
- Pulsar

Introduction to Division for Heliospheric Research

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, the global structure of the heliosphere, and its variation. Also, laboratory and fieldwork experiments are performed for improving data quality and upgrading the instruments.

Main Achievements in FY2017

1. Solar wind observations using the IPS system

We have performed 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 the 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.

2. International collaboration for space weather forecast

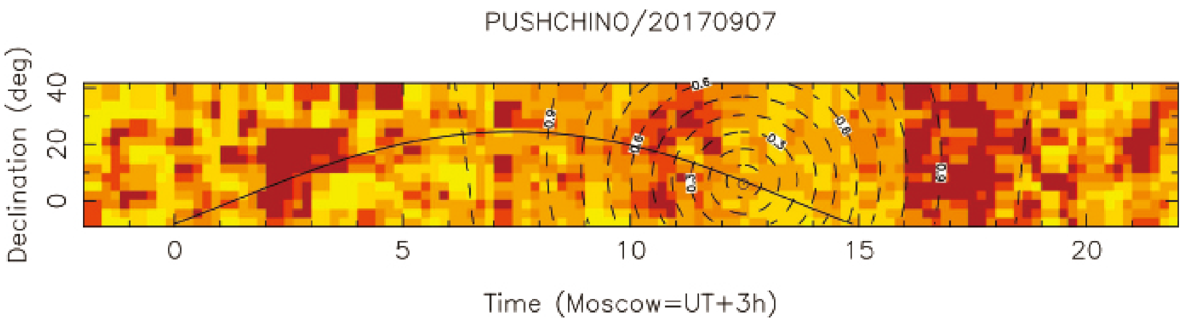
We have performed collaborative research with Dr. B. V. Jackson and his colleagues at the University of California, San Diego (UCSD) on 3D reconstruction of the time-varying heliosphere using tomographic analysis of IPS observations over a long period. The time-dependent tomography (TDT) program was 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 realtime at the Korean Space Weather Center (KSWC) to predict the solar wind at the Earth. A prediction system for the solar wind and IMF at the Earth was also developed at KSWC combining TDT analysis of IPS data with the ENLIL solar wind model (Dr. D. Odstrcil of GMU/NASA). The ISEE signed an agreement on research exchange and cooperation with KSWC in 2012, and renewed this in 2016. In this FY, several people including the KSWC Director visited the Toyokawa observatory and discussed further collaboration.

3. World-wide IPS Stations (WIPSS) Project

As awareness grows of the utility of IPS observations for space weather forecasting, an increasing number of IPS observations have been conducted around the world. In addition to 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. 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 World-wide IPS Stations (WIPSS) was proposed at the IPS workshop held at Morelia, Mexico, in 2015, and research activities on IPS observations at each WIPSS station were reported at the IPS workshop in Cardiff in December 2017. Our IPS data are in the IPSDCF V1.1 format, which is a revision of the common data format defined at the UCSD IPS workshop in December 2016, and was made available via the ISEE ftp server. Comparison between IPS data at different stations is key to realisation of WIPSS. We invited Dr. Sergey Tyul'bashev from the Pushchino Radio Astronomy Observatory (PRAO) in Russia to our laboratory for the period September 10–December 9, 2017, and compared IPS data obtained from the Big Scanning Array at PRAOP with those from ISEE. In addition, Dr. P. K. Manoharan of the Ooty Radio Astronomy Center (India) visited our laboratory from March 11–30, 2018, and compared Ooty and ISEE IPS data.

4. Coordinated Observations of interplanetary disturbances in Japan and Russia

A marked enhancement in solar flare activity occurred in early September 2017, leading to two halo coronal mass ejections (CMEs). Travelling interplanetary disturbances associated with the halo CME events on September 4 and 6, 2017, were clearly detected in IPS observations at ISEE, Japan, and PRAO, Russia. We compared ISEE and PRAO IPS data for these events, considering the longitudinal difference between the two stations. We found that both data sets were consistently explained by disturbances propagating toward the Earth at high speed. The IPS data for the CME



All-sky map of the solar wind density disturbance index derived from IPS observations at PRAO, Russia, on September 7, 2017.

events on September 4 and 6 show that the average transit speeds of disturbances were as high as >1000 km/s. This is higher than the average speed of the IPS shocks arriving at the Earth, suggesting that the disturbances decelerated during the propagation. Slowly (~700 km/s) moving disturbances were also observed in the September 6 event, following the fast disturbances. The slowly moving disturbances can be explained by a flank of the disturbances that propagated more slowly than the central portion. The result obtained here demonstrates the utility of the world-wide IPS observation network for space weather forecasting.

5. Long-term variation of very-slow solar wind with low density

Solar wind with a speed less than 350 km/s is called very slow solar wind (VSSW), and our past study showed that its source corresponds to the region near the active region, where the magnetic field is connected to interplanetary space: the so called open region. The efficiency of the acceleration mechanism for the VSSW is considered to be less than that for the ordinary slow wind owing to the extremely large expansion factor of the magnetic flux of the open region. We investigated the long-term variation of the solar wind density fluctuation level ΔNe using ISEE IPS observations obtained over many years. We found that the occurrence rate of the VSSW associated with low ΔNe increases markedly during the period between Cycles 23 and 24. Since ΔNe is roughly proportional to the solar wind density, our finding suggests that the VSSW of Cycle 24 is significantly rarefied. We also investigated *in situ* observations made from the ACE spacecraft, and found that the occurrence rate of the low density VSSW increases in Cycle 24, consistent with the IPS observations. We investigated the properties of the magnetic field at the source region of the VSSW associated with ΔNe using the potential field model, and found that the source region of the low ΔNe VSSW is associated with smaller expansion factors and weaker magnetic fields than that of the high ΔNe VSSW. This suggests that the low density VSSW that increased in occurrence frequency in Cycle 24 corresponds to the pseudo-streamer formed in the quiet Sun region.

6. On the origin of extremely non-radial solar wind outflows

The solar wind is primarily radial in nature with the azimuthal component of the flow typically being between 10–30 km/sec. However, non-radial flows (azimuthal flow angle > 60) are observed on many occasions. Although non-radial flow associated with solar wind disappearance events has been noted previously, the causes of the non-radial flow have not been addressed. The degree of deviation from the radial direction also has consequences for geo-effectiveness and space weather, and we have therefore investigated a large number of such cases in Cycles 23–24, covering the period 1995–2017. In all the cases, the azimuthal angle of the solar wind flow exceeded more than 6o for a period of 1 day or more in the absence of any solar phenomena such as CME and/or co-rotating interaction regions (CIRs). For most of the events, the solar wind density at 1 AU was < 5 cm^{-3} for periods of more than 1 day, similar to the well-known ‘‘solar wind disappearance events’’, which show unusual drops in solar wind density at 1 AU (< 1 cm^{-3}) for prolonged periods (> 1 day). The significant changes in the charge state ratio of O^{7+}/O^{6+} at 1 AU, for most of the events, suggest fast and dynamic evolutions taking place at the source regions. We thus traced the events back to the Sun, using a velocity trace-back technique combined with a potential field source surface extrapolation, to pinpoint their solar sources. Strikingly, this exercise revealed that the events are associated with characteristic pairings of active regions (AR) and coronal holes (CH) located at the central meridian. The dynamical evolution taking place at the AR-CH complex regions was examined, using the Extreme Ultraviolet Imaging Telescope and the Michelson Doppler Imager images, and shows new emerging magnetic flux regions and coronal loops during the trace-back dates, disturbing the stable CH configurations and leading to the extreme non-radial events. Therefore, this investigation showed for the first time the causative mechanism of non-radial solar wind flows that are not associated with CME or CIR. This work was carried out in collaboration with the Physical Research Laboratory, India, under the ISEE International Collaborative Research Program.

7. Estimation of magnetic flux rope axis orientation at 1 AU using the cylinder and the toroidal model

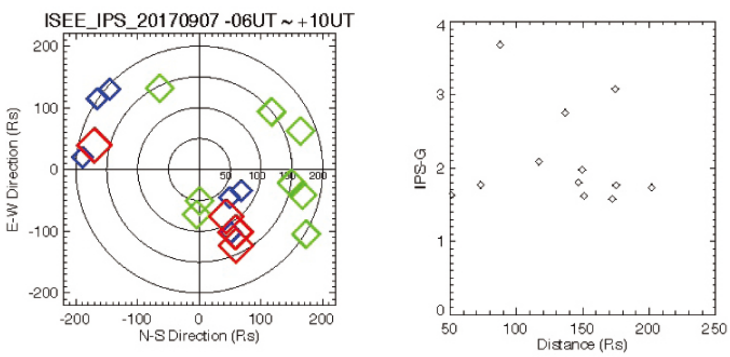
CMEs are large expulsions of magnetized plasma from the Sun. The magnetic field structure inside CMEs consists of a bundle of helical magnetic field lines around the central axis, known as the magnetic flux rope (MFR). The axis orientation of MFRs is an important factor in space weather forecasting. Estimation methods for the axis orientation include the cylinder and the toroidal model fittings. The cylinder model is characterized by a straight axis surrounded by helical magnetic field lines and the toroidal model is characterized by a curved axis. We analyzed five MFR events observed by the ACE spacecraft during 2006 and 2007, and used both the cylinder and toroidal models to investigate the possibility of curvature of the MFR axis. The toroidal model yielded an axis orientation similar to (less than 11 deg) that of the cylinder model for two MC events, a little different (near 30 deg) for one event, and significantly different (greater than 90 deg) for one event; the remaining event could be fitted well only by the toroidal model.

8. Measurement of coronal density using the Crab pulsar

In recent years, the decrease in solar wind density due to declining solar activity has been highlighted from IPS and *in situ* observations. Coronal observations, which provide the source of the solar wind, are important for investigating solar activity. We aimed to estimate the coronal density using the dispersion measure (DM) of the Crab pulsar. The DM is the frequency dispersion observed in the pulsar signal, which gives the integrated plasma density along the line-of-sight (los). The los of the Crab approaches the Sun in mid-June, to as close as 5 solar radii over the South Pole. By taking the difference between the DMs when the los of the Crab is located close to and far from the Sun, it is possible to determine the (integrated) coronal density over the South Pole. Crab observation has been conducted at the Toyokawa observatory since November 2016. The Crab is also known to emit exceptionally bright pulses called giant pulses, and these enable rapid DM estimation. We detected tens to hundreds of giant pulses each day, many more than previous studies, which indicates the high sensitivity of the radio telescope at Toyokawa (SWIFT). We are working on development of further pulsar observations using SWIFT.

9. IPS data driven simulation for real-time space weather forecasting

The solar wind and CMEs sometimes cause disturbances in geospace that are closely related to the social life such as radio telecommunications, spacecraft and airplane operation, and GPS navigation. Forecasting of geospace disturbances, i.e., space weather, has therefore become increasingly important. The IPS observations at ISEE detect CMEs and high-speed solar winds from stable ground-based radio observations. We have begun development of an IPS data-driven MHD simulation system under a joint research program with the National Institute of Information and Communications Technology (NICT), which organizes the Japanese space weather forecasting center. MHD simulation by NICT can estimate CME propagation in interplanetary space using initial conditions given by white light coronagraph images; IPS observations can be used to derive the locations and speeds of CMEs in the interplanetary space. In our IPS data-driven MHD simulation system, many possible propagation patterns of a CME are calculated, then the IPS level is calculated using the 3D electron density variation derived from each MHD simulation. The most probable CME propagation is derived by comparing the calculated IPS results with the observed IPS results.



Left: IPS disturbances of a CME derived by the IPS observation of ISEE.
Right: Location of the CME derived by the IPS observation.