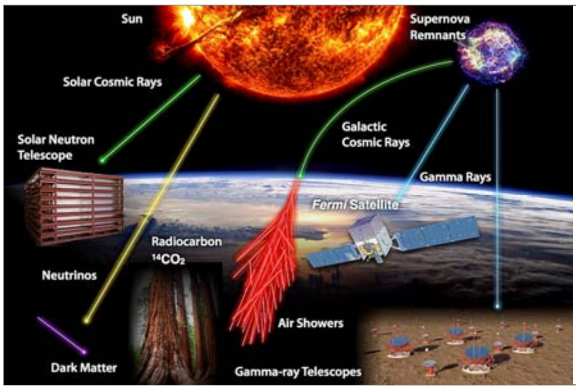
Division for Cosmic-Ray Research



- Acceleration and propagation of cosmic rays
  - Cosmic gamma-ray observations
  - Solar neutron observations
- Cosmic-ray interactions with the Earth’s atmosphere
  - Hadron interactions of very-high-energy cosmic rays
  - Past solar activities probed by cosmogenic nuclides
- Particle astrophysics and non-accelerator physics
  - Dark matter and neutrino physics
- Wide-field transient survey by an optical telescope

Cosmic rays (CRs), which are mostly protons with small amounts of charged particles, such as electrons or nuclei, and neutral particles, such as gamma rays or neutrinos, are produced in space and propagate through interstellar and interplanetary magnetic fields before reaching the Earth. The Division for Cosmic-Ray Research performs cosmic gamma-ray observations using the Fermi Gamma-ray Space Telescope (Fermi satellite) and the Cherenkov Telescope Array (CTA), as well as high-altitude solar neutron observations, to reveal the CR acceleration mechanisms as common space plasma phenomena.

CRs also provide hints for ultra-high energy phenomena and unknown particles that cannot be explored in a laboratory. We conducted the Large Hadron Collider forward (LHCf) and the Relativistic Heavy Ion Collider forward (RHICf) experiments to study the hadronic interactions of ultra-high energy CRs using accelerators such as LHC or RHIC. This division also conducts neutrino physics research with the Super-Kamiokande experiment and promotes the Hyper-Kamiokande project as a future prospect. The group intensively works for direct dark matter searches in the XMASS liquid xenon experiment at the Kamioka Observatory and has recently started a new commitment to the XENONnT experiment in LNGS in Italy.

CRs deeply penetrate the atmosphere, producing ionization and cosmogenic nuclides. Our division studies past solar activities and sudden changes in CR flux that are recorded in the carbon-14 (^{14}C) fractions of ancient tree rings and other cosmogenic nuclides from Antarctic ice cores.

In addition, this division conducts the MOA experiment with a dedicated 1.8-m wide-field optical telescope at Mt. John University Observatory in Tekapo, New Zealand. It conducts surveys of gravitational microlensing due to massive astrophysical compact halo objects (MACHOs) or exoplanets and optical follow-up observations of gamma-ray bursts, super-nova neutrino detections, and gravitational wave events.

Main Activities in FY2018

Search for dark matter and research on the origin of cosmic rays with gamma-ray observations

Cosmic gamma rays are expected to be produced through interactions of dark matter, CRs, and the interstellar medium. It makes gamma rays good probes to search for dark matter and to investigate the properties and distributions of CRs and the interstellar medium.

We have been developing an image restoration technique for Fermi gamma-ray data. We improved this technique to account for the Galactic diffuse gamma-ray background. This enables image analysis of faint gamma-ray sources in the presence of the diffuse gamma-ray background. By applying this technique in the Galactic center region, we found possible new gamma-ray sources that have not been previously detected. This is a step forward for better understanding of backgrounds for dark-matter search in this region. We also applied this technique to image the supernova remnant, RX J1713.7–3946. We have found an image slightly different from that obtained by higher-energy gamma rays. These results are presented in the Fermi symposium 2019.

We are developing the next-generation gamma-ray observatory, the CTA, to observe gamma rays at higher energies than the Fermi satellite. We are in charge of the development of silicon photomultipliers (SiPMs) for the Gamma-ray Cherenkov Telescope, which is a CTA telescope. We systematically characterized SiPMs with different geometries and finalized the specifications based on the measurement results. We also developed calibration procedures for gain characterization and stabilization against temperature excursions.

Group photo at the inauguration of the SCT prototype on Jan. 17, 2019. (Image credit: Deivid Ribeiro, Columbia University)

In addition, we started studying the feasibility of replacing the photomultipliers (PMTs) with SiPMs for the medium-sized telescopes (MSTs) of the CTA. Originally, the PMT was selected as it was less expensive for covering the area required for the MST camera. As the SiPM cost became comparable to the PMT cost, the SiPM became an attractive alternative because it can operate under the moonlight, which can double the observation time of the MST. The simulation study that takes into account the wavelength dependence of the photon detection efficiencies of SiPMs and PMTs indicates that the overall efficiencies for Cherenkov photons are very similar between them. We are now verifying the properties (mainly angular and spectral dependence) of the SiPM and PMT to adjust the simulation.

We also contributed to the development of signal processing electronics for the Schwarzschild-Couder telescopes (SCTs) and light concentrators for photosensors of the large-sized telescopes (LSTs). Prototypes of the SCT and the LST were constructed and succeeded in taking Cherenkov images of air showers produced by interactions of cosmic rays.

Acceleration mechanism of solar energetic particles

The study of the acceleration mechanism of solar energetic particles is expected to provide key information for understanding the origin of CRs. To understand particle acceleration at the Sun, it is necessary to know the moment and duration of particle acceleration at the solar surface. Solar neutrons produced at the solar surface through the interaction of accelerated ions with the solar atmosphere are studied at ISEE. Neutrons are not reflected by the interplanetary magnetic field, and are thought to be preferable over accelerated particles themselves for studying the acceleration mechanism of solar energetic particles. The emission timing of neutrons can be determined from the neutron energies. ISEE has developed a worldwide network of solar neutron telescopes to detect solar neutrons (>100 MeV) over an entire day. Following the ceasing of the operation at Gornergrat in Switzerland in fiscal year (FY) 2017, the operation at Mauna Kea in Hawaii also ceased in FY2018.

Besides this network, a new solar neutron telescope was installed in Sierra Negra, Mexico (97°W, 4600 m), in 2013. The new detector was previously used for accelerator experiments, and uses 15,000 scintillator bars to measure particle tracks, providing much higher energy resolution and better particle discrimination than previous solar neutron telescopes. The new telescope was built with the support of Kyoto University, High Energy Accelerator Research Organization (KEK), and the National Autonomous University of Mexico, and the experiment was called the SciBar Cosmic Ray Telescope (SciCRT). Our Monte Carlo simulation study predicted that the power-law index of the solar-neutron energy spectrum can be determined to an accuracy of 0:1 if we know the duration of neutron production at the solar surface. Moreover, if an ambiguity of up to 1:0 of the power-law index is permitted, it is possible to discriminate between an instant emission and a continuous emission of longer than 5 min.

The activity of solar cycle 24 reached a maximum in February 2014 and has since decreased. No solar-neutron events were detected in FY2018. Significantly, two large solar flares occurred in September 2017, and their soft X-ray fluxes measured by the GOES satellite were the two highest values in solar cycle 24. Unfortunately, solar neutrons were not recorded in these flares, but we obtained four sigma excess of neutrons by SciCRT associated with a smaller solar flare, which occurred between these two large flares. Detailed analyses using information on particle tracks are underway.

This study was performed in collaboration with Chubu University, Shinshu University, the National Astronomical Observatory of Japan, RIKEN, the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo, Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency (ISAS/JAXA), the Japan Atomic Energy Agency (JAEA), the National Defense Academy, the Aichi Institute of Technology, and many other institutions around the world.

Cosmic-ray interaction-focused accelerator experiment

Hadronic interactions of cosmic rays play many important roles from the aspect of astroparticle physics. They interact with interstellar matter and produce cosmic gamma rays or neutrinos, through which multi-messenger particles, various cosmic ray physics, and astrophysics are studied. In addition, high-energy cosmic rays repeat interactions in the atmosphere and are observed as particle clusters called “air showers” at the ground. To extract information of cosmic rays from “air showers,” implication based on the correct knowledge of hadronic interactions is needed. They can be studied by various accelerator-based experiments. For example, hadron collider machines, such as the LHC at CERN or RHIC at Brookhaven National Laboratory (BNL), provide an opportunity to study hadronic interactions equivalent to cosmic rays of 10^{14} to 10^{17} eV.

In FY2018, we continued data analysis of the RHICf experiment obtained in 2017 run for the polarized proton–proton collisions at 510 GeV. We first reported transverse asymmetry in the very forward productions of neutral pions, which was a totally unexpected new phenomenon. We continued ATLAS-LHCf-combined analysis of proton–proton collision data at $\sqrt{s}$=13 TeV collected in 2015 at LHC and reported a detailed analysis of diffraction processes and its effect on air shower development. We also started discussion on the future data-taking plan of LHCf at LHC-RUN3 foreseen at 2021, especially from the aspect of the first combined data-taking of LHCf with ATLAS Roman-pot detectors.

Cosmic neutrinos and dark matter

A neutrino is a neutral elementary particle with an infinitesimal mass, which is scattered only through the weak interaction. The strong penetrating power of neutrinos means that information from the center of celestial bodies, such as the Sun and Earth, can be determined. In addition, neutrino oscillation occurs because of the quantum-state mixing between the three neutrino flavors. By observing this oscillation, we can explore unknown properties of neutrinos, such as their masses and mixing, and hidden information such as the material density of celestial bodies. Besides neutrinos, there are thought to be particle dark matter (weakly interacting massive particles, WIMPs) in the universe. Many experimental efforts elsewhere need to be conducted to detect its evidence for the first time.

In FY2018, we worked inside the Super-K tank after 13 years since the last access to the tank. Bad photomultipliers were replaced and the entire tank structure was cleaned up to prepare for the Gd-loading work foreseen for the next year. Since January 2019, Super-K has been filled up with pure water and resumed data-taking. As for the development of Super-K analysis, we continue development of the muon neutrino/muon anti-neutrino separation technique with the use of decay electrons from muon decays and neutron emission from neutrino interactions. We have been promoting a next-generation ultra-large water Cherenkov detector, Hyper-Kamiokande, with fiducial volume 8 times greater than that of Super-Kamiokande. A substantial effort for organization of the project has been continuously made as a member of the international Steering Committee.

We have conducted the XMASS experiment for direct WIMP searching using an ultra-low background liquid-xenon detector. The experiment has completed data-taking in January 2018 and now all the xenon has been collected. As a next step, we join the world's largest liquid xenon dark matter search experiment XENONnT from December 2017. We have started contribution to the development of a neutron veto detector by using the Ga-loading water Cherenkov technique and a liquid xenon purity monitor. In addition, we have developed a liquid-xenon single-phase TPC. We successfully observed the first S2 signal for the 13.9 keV line, which is the lowest energy ever reported for the single-phase detector. We also successfully achieved electron-recoil/nuclear-recoil separation using the S1/S2 ratio for the first time for the single-phase liquid xenon TPC.

Historic cosmic-ray intensity variation with cosmogenic radioisotopes

Cosmic rays falling on the Earth interact with the atmosphere and produce various secondary particles. Among them, long-lived cosmogenic nuclides, such as ^{14}C and ^{10}Be, are used as excellent proxies for cosmic-ray intensities in the past. We measured ^{14}C concentrations in tree rings and ^{10}Be concentrations in ice cores to investigate past cosmic-ray variations. In particular, we aim to clarify the frequency of extreme solar proton events, which would cause sudden and large increases in cosmic-ray flux to the Earth.

We discovered the annual cosmic-ray increase events in AD 775 and 994 from ^{14}C analyses of Japanese tree rings. The discovery of these events led to the accumulation of annual ^{14}C data during extended measurement periods as background to further event surveys. In this year, we have taken almost all continuous annual ^{14}C data for the past 3000 years. During this period, it has become apparent that there are at least three sharp increases in ^{14}C concentrations. In addition, we detected a sharp rise in ^{14}C concentrations around 800 BC and discussed the cause, as a collaboration research with the University of Arizona group. In addition, we elucidated the details of ^{14}C variations of the 775 and 994 events by using worldwide tree samples (COSMIC project; Büntgen et al. 2018). We clarified the regional differences of ^{14}C variations, event start dates, and ^{14}C production rates to explain ^{14}C variations of the two events with high accuracy. The obtained worldwide data showed a latitude dependence on ^{14}C concentrations, which suggests that the original particles are charged particles affected by the geomagnetic field, thus supporting the solar proton origin. To investigate the cause of the 994 event, we measured quasi-annual ^{10}Be concentrations in the Antarctic Dome Fuji ice core and showed that the detected ^{10}Be increment is consistent with the peaks found in the Greenland ice cores. Almost the same amount of ^{10}Be increases in both hemispheres suggests the charged particle origin for the 994 event.

Cloud-formation experiment irradiated by heavy nuclei beams

As a conjecture for explaining the possible correlation between the Schwabe cycle of the Sun and the Earth climate, there has been discussion for possible cloud formation enhanced by galactic cosmic rays. We conducted an experiment using a small reaction chamber filled with air irradiated by ion beams such as protons, nitrogen, and xenon nuclei at the HIMAC accelerator in the National Institute of Radiological Science, Chiba, Japan. We analyzed the obtained data in detail to investigate the correlation between nuclear creation rates and ionization density (dE/dx). We found the nuclear creation rate simply scaled by the total dose to be irrelevant to the difference in the beams, i.e., ionization density. We are now summarizing an article to report it.

Wide-field optical surveys for gravitational microlensing and gravitational sources

In 2018, we detected 413 microlensing events and issued real-time alerts to follow-up groups. Several candidates of extrasolar planets have been found, and their analyses are in progress. The new gravitational wave observation period O3 will start in March 2019. Preparation for next gravitational observation is in progress.