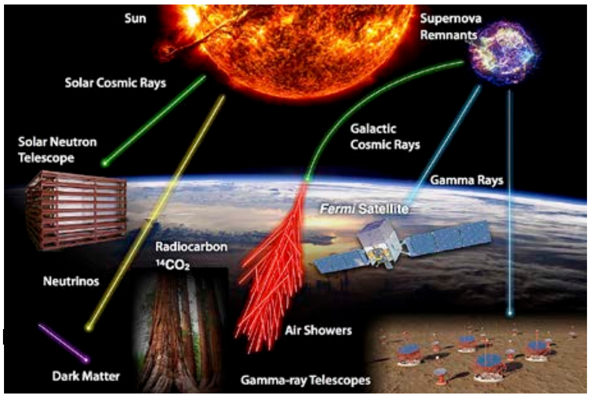
9-1. Research Divisions
Division for Cosmic-Ray Research



Research topics and keywords

- 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
- Wide-field transient survey by an optical telescope

Introduction to Division for Cosmic-Ray Research

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), and 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 conduct Large Hadron Collider forward (LHCf) and Relativistic Heavy Ion Collider forward (RHICf) experiments to study hadronic interactions of ultra-high energy CRs using the Large Hadron Collider (LHC) and Relativistic Heavy Ion Collider (RHIC) accelerators, respectively. This division also conducts neutrino physics research with the Super-Kamiokande experiment, and promotes the Hyper-Kamiokande project as a future project. We intensively work for direct dark matter searches in the XMASS liquid xenon experiment at the Kamioka Observatory, and recently started 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 of the CR flux that are recorded in the carbon-14 (^{14}C) concentration of ancient tree rings and other cosmogenic nuclides from Antarctic ice cores.

In addition, this division conducts the MOA project 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 caused by massive astrophysical compact halo objects (MACHOs) or exoplanets, and optical follow-up observations of gamma-ray bursts, supernova neutrino detections and gravitational wave events.

Main Achievements in FY2017

1. Search for the origin of cosmic rays with gamma-ray observations

Cosmic gamma rays are good probes for investigating the properties and distributions of CRs and the interstellar medium, since gamma rays are produced by their interactions. Supernova remnants (SNRs) are the leading candidate for the origin of Galactic CRs. Past gamma-ray observations from the Fermi satellite confirmed that CR protons are accelerated to GeV energies in SNRs with ages older than 10,000 years. However, we have not resolved the mechanism of particle acceleration or obtained the maximum energy of particles accelerated by SNRs.

We are developing the Gamma-ray Cherenkov Telescope (GCT), which is one of the telescopes for the next generation of the gamma-ray observatory, the CTA, to address these questions. We are in charge of the development of silicon photomultipliers (SiPMs) for GCT. We found that the resin coating for SiPM surface protection was causing degradation of optical crosstalk, one of the key parameters of the SiPMs. We are now improving the handling of the SiPMs during camera assembly so that the protection resin can be removed; we are also re-optimizing the geometry of the SiPM internal structure to take advantage of better crosstalk.

Gamma rays are also useful for studying the distribution of interstellar gas, since gamma-ray intensity is well correlated with gas density. Recent observations by the *Planck* satellite have provided unprecedented measurements of all-sky dust distributions with 10-arcminute resolution using the attenuation coefficient for 353-GHz microwaves. The amount of dust is correlated with the amount of gas, which can be verified by measurement of the correlation between the dust and gamma rays. We found that the attenuation coefficient for 353-GHz microwaves correlated well with the gamma-ray intensity in the MBM 53–55, Pegasus Loop and Chameleon regions. In these studies, we found nonlinearity between those correlations. Further studies are ongoing to model the nonlinearity in the Orion region, since this region contains a wide range of matter density, which is suitable for the nonlinearity study.

We have improved the image restoration technique used for the *Fermi* gamma-ray data to account for the Galactic diffuse gamma-ray background, which enables image analysis of faint gamma-ray sources. By applying this technique in the Galactic center region, we found possible new gamma-ray sources that have not been previously detected. Further analysis is in progress.

2. Research on the acceleration mechanism of solar energetic particles

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 to 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. In fiscal year (FY) 2017, operation at Gornergrat in Switzerland ceased.

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 is 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 minutes.

The activity of solar cycle 24 reached a maximum in February 2014, and has since decreased. No solar-neutron events have been detected in FY 2017. 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 may have detected solar neutrons if these flares had occurred at noon in Mexico.

This work 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.

3. Study of cosmic neutrinos and dark matter

The neutrino is a neutral elementary particle with an infinitesimal mass, which is scattered only via weak interaction, and its strong penetrating power can provide physical information from the center of celestial bodies such as the Sun and the Earth. In addition, by observing neutrino oscillations, which occur because of quantum state mixing between the three neutrino species, we can explore unknown properties of neutrinos, such as their masses, and hidden information, such as the material density of celestial bodies. In addition to neutrinos, which only weakly interact with other particles, particle dark matter (weakly interacting massive particles, or WIMPs) are thought to exist in space and many projects are working on first detection.

In 2017, a new technique to separate muon neutrinos and muon anti-neutrinos was developed through use of decay-electrons from muon decays, and neutron emission from neutrino interactions. The separation performance has been evaluated and looks promising. Further application to atmospheric neutrino oscillations in matter is now being considered. We have been promoting a next-generation ultralarge water Cherenkov detector, Hyper-Kamiokande, which has a volume 20 times greater than that of Super-Kamiokande. We have made substantial and continuous efforts toward organization of the project, as one of the main stakeholders.

We have conducted the XMASS experiment for direct WIMP searching using an ultra-low background liquid-xenon detector. We have studied a new scheme for nuclear recoil detection by electron emission via the Migdal effect, and an intensive study of neutron calibration data has been made to detect the possible Migdal effect. In addition, for application to future largescale dark-matter-search experiments, we have developed a liquid-xenon single-phase TPC. Some XMASS members have become new participants in the XENONnT experiment, the world’s largest liquid-xenon dark-matter detector, foreseen to be operational by 2019. Contribution to the neutron-veto system and purification of xenon has been discussed.

4. Cosmic-ray interaction-focused accelerator experiment

Hadronic interactions of CRs play many important roles in cosmic-ray physics. CRs interact with the interstellar medium and produce cosmic gamma rays or neutrinos through which a range of CR astrophysics can be studied. High-energy CRs undergo repeat interactions in the atmosphere that are observed as particle clusters called “air showers” at the ground. To extract CR information from air showers, precise knowledge of hadronic interactions is required, which can be studied through accelerator-based experiments; for example, hadron collider machines such as the LHC at the European Organization for Nuclear Research (CERN) or the RHIC at Brookhaven National Laboratory (BNL) provide an opportunity to study hadronic interactions equivalent to CR energies of 10^{14}–10^{17} eV.

In June 2017, the RHICf experiment successfully collected data during radially polarized proton–proton collisions with a collision energy of 0.51 TeV. In a quick analysis, we observed a clear peak of neutral pions in the invariant mass of two photons hitting the detector. A range of other analyses is now in development. The first combined analysis of the LHCf experiment with the ATLAS detector has been conducted using data for proton–proton collisions at $\sqrt{s}$ = 13 TeV collected at the LHC in 2015. This is an important milestone for study of diffractive interaction in the very-high-energy range, which is highly relevant to air-shower physics of very-high-energy CRs.

5. Historic cosmic-ray intensity variation with cosmogenic radioisotopes

Radiocarbon (^{14}C) concentrations in tree rings are a good proxy for historic CR intensity reaching the Earth. The CR flux may reflect short-term ($\leq$ 1 year) high-energy phenomena such as supernova explosions near the solar system or arrival of solar CRs by extreme solar proton events (SPEs). Although the CR flux variation in the past has been investigated by ^{14}C concentration measurements in tree rings with time resolutions of more than 10 years over the Holocene (the last 12,000 years), variations at 1 or 2-year resolutions have not been investigated for most periods. Several

CR increase events have been detected by ^{14}C measurements, e.g., the AD 775 and the AD 994 events published by our group in 2012 and 2013, respectively. This suggests a relationship between these CR events and extreme SPEs.

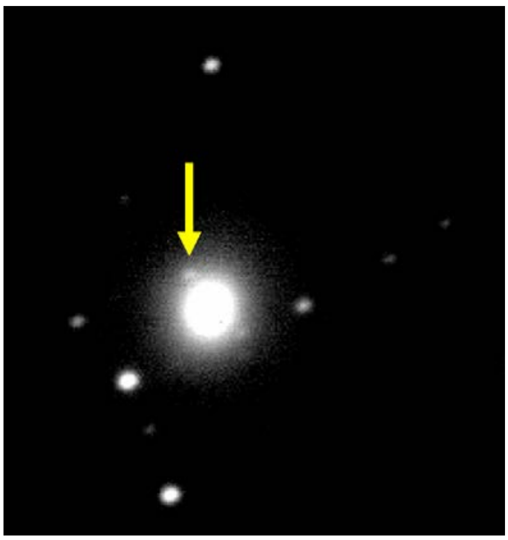
To investigate similar CR increase events occurring in the past 3,000 years, we measured ^{14}C contents in annual rings at biennial intervals using accelerator mass spectrometers (AMSs) at Nagoya University and Yamagata University, for the periods covering the 2nd–3rd AD centuries, the 1st–4th BC centuries, and the 9th–12th BC centuries. We obtained continuous ^{14}C data with annual resolution for most of the past 3,000 years, and found that the AD 775 event had the largest ^{14}C increment in the period. We also found two other events in AD 994 and 660 BC with scales almost half that of the AD 775 event. Although there are other small ^{14}C increases in the data, it is necessary to conduct additional verification to distinguish these small events from background variations.

6. Verification of the cosmic-ray-induced cloud formation hypothesis

We aimed to verify the increase in cloud condensation nuclei due to galactic CRs, as one hypothesis for the correlation mechanism between solar activity and the global climate. We investigated the relationship between the ionization density and the production efficiency of cloud nuclei formation with an atmospheric reaction chamber, by irradiation of high-energy protons, nitrogen, and xenon ions at the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS). The experimental data were carefully analyzed and showed that the particle density at the nanometer level in the atmosphere varies, corresponding to the ion density produced by high-energy heavy ions, and that they are possibly independent of the incident ion species, that is, the ionization density along the track. On the other hand, relatively high production efficiency was obtained for protons. For further discussion of the relationship between lower cloud amounts and the CR flux in the lower atmosphere, more precise experiments are necessary.

7. Wide-field optical surveys for gravitational microlensing and gravitational sources

In 2017, we detected 511 microlensing events and issued real-time alerts to follow-up groups. Analyses of the events are in progress. Discovery of the merger of a neutron star binary was conducted by the LIGO and Virgo detectors on August 17, 2017 (GW170817). We succeeded in observing its optical counterpart from the MOA II telescope 1.78 days after detection of the gravitational wave.

Left: The domes of the MOA II 1.8-m (left) and the B&C 61-cm telescopes.
Right: The optical counter part of the gravitational-wave event and its host galaxy NGC 4993 imaged by the MOA II telescope.