Six Years of cross-disciplinary studies at the Astro-Glaciology Research Unit: Astronomical signatures in polar ice cores

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Our Astro-Glaciology Research Unit (AGU), established on July 1, 2011, is the only group worldwide investigating the new cross-disciplinary research field of astro-glaciology, which combines astrophysics, climate science and solar-terrestrial physics, and glaciology, both experimentally and theoretically (Figs. 1 and 2).

Gamma rays, X-rays, and UV radiation arising from solar activity and supernova explosions in our galaxy cause changes in the chemical composition of the stratosphere (from $\sim 10 - 50$ km altitude). The effects of radiation on the stratosphere are then recorded in the chemical and isotopic composition of terrestrial ice.

An ice core is therefore a time capsule. The cylindrical ice core drilled by the Japanese Antarctic Research Expedition (JARE) at the Dome Fuji station in Antarctica is 3,035 m long and corresponds to a time period from 720,000 years ago to the present (Fig. 3). We have been studying the uppermost ∼100 m of an ice core that was recovered from the same hole as the deep ice core shown in Fig. 3 as well as another shallow ice core; both cases correspond to the last 2,000 years. A newly approved project to obtain an ice core corresponding to a 1,000,000 year period has already commenced.

Fig. 1. Our AGU group in the low temperature room (−30°C and −50°C) at NIPR (2012).

Fig. 2. Dr. Yoichi Nakai sampling an ice core in the low temperature room (−30°C) at NIPR (2012).

There are significant advantages in using Dome Fuji ice cores when studying astronomical phenomena of the past, because the effects of radiation on the stratosphere recorded in ice cores in the Dome Fuji area are more pronounced than in ice cores obtained from elsewhere on the earth.

Anions and cations in our ice cores were analyzed at RIKEN using an ultra-high-sensitivity ion chromatography technique[a)] (Fig. 4). The sulfate ion (SO_4^{2-}) concentration spikes indicate volcanic eruptions and can provide time markers for dating ice cores. The SO_4^{2-} spikes (Fig. 5) observed in Dome Fuji ice cores are an order of magnitude higher than those in a standard ice core drilled in West Antarctica.[b)] This demonstrates an important advantage when using our cores, since high volcanic SO_4^{2-} spikes imply a high level of inclusion of stratospheric components.

Collaboration between AGU and the National Institute of Polar Research (NIPR, Tokyo) involves analyzing ionic and isotopic concentrations in Dome Fuji ice cores. Our aim is to reveal in the ice cores:

(1) signatures of past solar cycles
(2) relationships between past solar activity and climatic changes
(3) footprints of past supernova explosions in our galaxy, in order to understand better the rate of galactic supernova explosions.

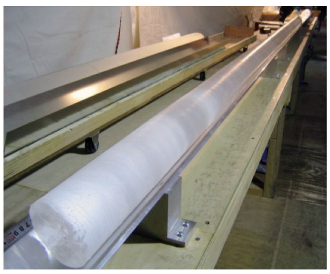

Fig. 3. A deep ice core drilled in 2007 at Dome Fuji station in inland Antarctica (photograph courtesy of NIPR).

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a) High-resolution chemical analysis of ice core samples from Dome Fuji station, Antarctica: Y. Motizuki, K. Takahashi et al.: Geochemical J. 51, 293-298 (2017) [Press-release]

b) 2000-yr record of volcanism: M. Sigl, Y. Motizuki et al.: Nature Climate Change 4, 693-697 (2014) [Press-release]

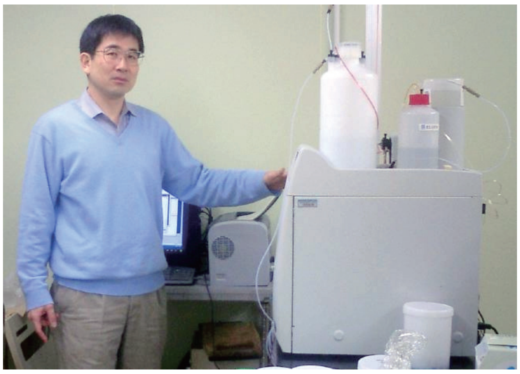

Fig. 4. Dr. Kazuya Takahashi with our first ultra-high-sensitivity anion chromatography detector (ICS2000 system) in a clean room at RIKEN (2006).

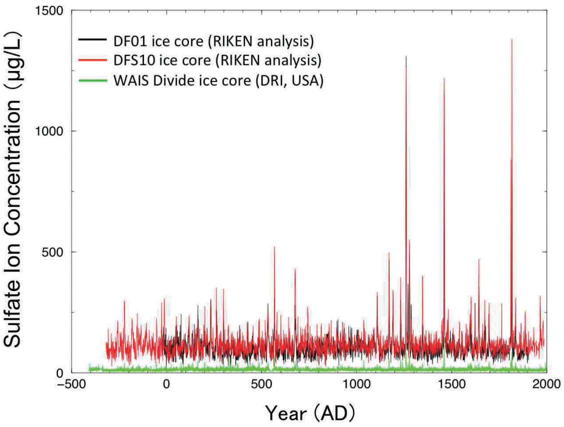

Fig. 5. SO_4^{2-} concentrations shown versus year (AD) for two Dome Fuji ice cores and a standard ice core drilled in West Antarctica (WAIS Divide, USA). The temporal resolution is ~1 year. Spikes represent volcanic activity.

We have succeeded in extracting periodicities that correspond with solar cycles from the annually-resolved nitrate ion (NO_3^-) concentrations in a Dome Fuji ice core, and we have found candidate NO_3^- spikes that correspond with supernova explosions in our galaxy. Since the dates of several NO_3^- spikes almost match the dates of galactic supernova explosions that have occurred in the last millennium, we conjecture that yearly-scale NO_3^- concentration spikes found in Dome Fuji ice cores can be treated as a candidate proxy for supernova explosions that have occurred in our galaxy. We have also discovered a strong statistical correlation ($r = 0.84$) between variations in solar activity and variations in the temperature proxy ($^{18}O/^{16}O$) in a segment of our ice core that corresponds to a pre-industrial period.

Theoretically-based numerical simulations and experimental evidence will be combined. We have simulated chemical compositional changes in the stratosphere induced by solar proton events [SPEs: the bombardment of the atmosphere by high-energy (~10 − 500 MeV) protons originating in solar flares], in collaboration with the National Institute of Environmental Science (Tsukuba). To do this, we developed a 1D box model, taking into account 752 reactions including ion chemistry.[1)] We are also developing a 3D chemical climate model with a view of studying changes in the chemical composition of the atmosphere and the effects on climate pertaining to past and future SPEs and supernovae in our galaxy.

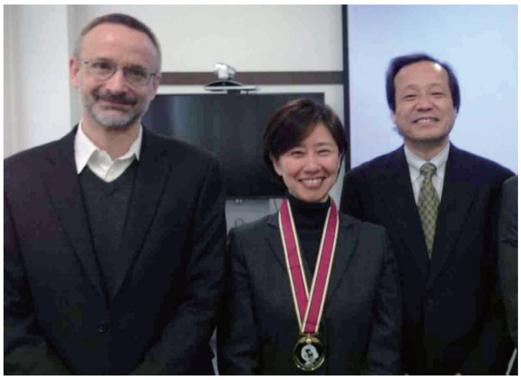

Fig. 6. Left to right: Prof. Marc Besancon (French Director, Toshiko Yuasa Laboratory (TYL)), Yuko Motizuki (AGU leader), and Prof. Junji Haba (Japanese Director, TYL) at TYL Gold Prize ceremony (Feb., 2017).

Cross-disciplinary collaboration between AGU and the RIKEN Center for Advanced Photonics has been initiated in order to develop an automated laser ice-core melting system. The system will make it possible to analyze deeper ice cores at a higher temporal resolution (~1 month), and it will thus become possible to investigate the galactic supernova rate and solar activity of the past 1,000,000 years.

The initial 3-year research project was supported by the Funding Program for Next Generation World-Leading Researchers (NEXT Program, Grant Number GR098) of the Council for Science and Technology Policy (CSTP). The project has been awarded an S-grade by CSTP (2015) within the NEXT Program.

Our research unit leader was awarded the Toshiko Yuasa Gold Prize in 2017 (Fig. 6), the theme being "Pioneering a new interdisciplinary research field regarding Antarctic ice cores and exemplifying leadership in academia"; and our leader was also granted Nice Step Scientist Certificate by MEXT National Institute Science and Technology Policy (NISTEP) in 2015.

Two postdoctoral researchers have participated, and four undergraduates and two postgraduate students have received degrees during this research project.

Reference

1) see, e.g., Y. Nakai, Y. Motizuki et al.: in this volume.