Planetary plasma and atmospheres explored by space missions in Japan: Hisaki, Akatsuki, and beyond

Y Kasaba¹, T Imamura², F Tsuchiya¹, N Terada¹, Y Miyoshi³, Y Kasai⁴, and Y Saito⁵

¹Tohoku University, Japan
²University of Tokyo, Japan
³Nagoya University, Japan
⁴National Institute of Information and Communications Technology, Japan
⁵Japan Aerospace Exploration Agency, Japan
E-mail: kasaba@pat.gp.tohoku.ac.jp

Abstract. Planetary plasma and atmospheres have been challenged by space missions of Japanese science community from 1990s, with ISAS and JAXA. The first trial, a Martian orbiter Nozomi, was launched in July 1998. At the departure from Earth in Dec. 1998, she met an engine trouble but we struggled and found a narrow and long path connecting to the Dec 2003 arrival, which is the simultaneous arrival with ESA Mars Express. Unfortunately, we had an additional power trouble in Apr. 2002 associated with a solar flare event, and we gave up the trial at the gate of Mars in Dec. 2003. In parallel to the Kaguya Lunar orbiter in 2007-2009, a next trial to planets, the Akatsuki orbiter to Venus, was prepared. She departed from Earth in May 2010. However, she got an engine trouble at the arrival to Venus in Dec. 2010, and we again endured another long path, but this road was at last ended by a success of the orbit entry in Dec. 2015. We also created the UV/EUV space telescope, Hisaki, using the sensor and optics technologies extracted from Nozomi. It is going well after the launch in 2013 and actively looking planetary thin atmospheres collaborating with other space missions. This paper summarizes the Hisaki and Akatsuki missions which are now on orbit, with the next missions, Arase (ERG), BepiColombo, JUICE, and beyond.

1. Hisaki, a UV/EUV space telescope dedicated to planetary exospheres
The first success from planetary plasma and atmosphere by ISAS (Institute of Space and Astronautical Science) and JAXA (Japan Aerospace and Exploration Agency) was achieved by a spacecraft on the terrestrial orbit, Hisaki UV/EUV space telescope, launched in September 2013 [1]. Its Extreme Ultraviolet spectrograph, EXCEED, provides the spectral images (520–1,480 Å) of tenuous gas and plasmas. We have used this telescope for the continuous observation campaigns of planetary magnetosphere, ionosphere, and exosphere and tried the long-term dataset for days to months, which are not easy even by the planetary orbiters and ground-based telescopes.

First targets were giant planets. Hisaki has a unique capability optimized to the long-term monitoring of H₂ aurora total flux in UV and the emission of satellite-origin gas and plasma clouds in EUV. Jupiter has a huge magnetosphere, driven by the plasma supply from the volcanic activities of Io with a typical rate of 1 ton/sec. Plasmas from Io plasma torus is transported outward and extracting huge energies from the Jovian fast rotation with strong magnetic field. Hisaki’s 3-month observations...
per year were coordinated in 2013-2016 with Hubble Space Telescope (UV), X-ray space telescopes, and ground-based Visible-Infrared observatories. Those results are summarized in another paper in the proceedings [2]. In 2016-2017, Hisaki’s priority is on the support observation of NASA Juno orbiter. For Saturn, water plume is supplied from Enceladus. We have examined the temporal and spatial variations of neutral oxygen produced associated with this plume [3].

For terrestrial planets, Hisaki tried to grasp the variation of oxygen and related molecules in ionospheres and exospheres, which are connected to the amount and process of atmospheric escape. Since Mars and Venus have weaker intrinsic magnetic dipole moments than Earth, their upper atmospheres are directly affected by solar wind collisions and can escape to space. Since solar activity could be more active in the early days, the knowledge of the solar wind effect on their upper atmospheres in current condition is the basic information for the estimation for the atmospheric evolution in those days, which can also be affected from the lower atmospheric conditions. For Venus, the variations of the dayglow brightness for OII 83.4 nm, OI 130.4 nm and OI 135.6 nm in the Venus’ thermosphere was detected [4]. Those emissions vary similarly with the variations of the solar EUV radiation flux. And other periodicities with 1-13 days were also identified and assumed as the density oscillations of oxygen atoms or photoelectrons in the thermosphere modulated by gravity waves and/or planetary-scale waves propagating from the lower atmosphere (figure 1). Extension of these studies is planned with the cloud-deck turbulence observations by Akatsuki (see Sec. 2). Martian observation was also tried and the upper limit of the ionospheric and exospheric emissions will be determined, collaborated with the upper atmospheric observations by NASA MAVEN orbiter.

2. Akatsuki, a Venus climate orbiter

Akatsuki was designed as the 2nd planetary orbiter following Nozomi, to investigate the meteorological processes. The orbiter was launched in May 2010, and once reached Venus in December 2010. However, by the trouble of its orbital maneuver engine, its orbit insertion failed. As the result, Akatsuki was forced the long travel as Nozomi. But this 5-years tour was successfully finished in December 2015. Although the failed engine could not be used, Akatsuki went into the initial orbit on a westward, elongated equatorial orbit with an apoapsis altitude of ~440,000 km [5]. Now, the scientific operation is on the orbit with the apoapsis altitude of ~360,000 km, a periapsis altitude of 1,000–8,000 km, and an orbital period of 10.5 days, respectively. It is not the same one planned before the launch, the current orbit is still suitable to take continuous global images of the full Venusian disks in ultraviolet (UV), near infrared (NIR), and mid infrared (MIR), like terrestrial meteorological satellites. The observed multi-wavelength images contain the information of the top (mesosphere) and the base (troposphere) of thick cloud decks, with the temporal and spatial resolution of 10s km and 1-2 hours, and provides the capability of continuous wind vector tracking.

By the combination of five imaging instruments aboard Akatsuki, multiple height levels of the atmosphere can be sensed. The lower atmosphere and the surface on the nightside are investigated by the 1-μm micrometer Camera (IR1). The middle and lower cloud region is covered by IR1 in the dayside and by the 2-μm Camera (IR2) in the nightside. The dayside cloud top is observed by the Ultraviolet Imager (UVI) and IR2. The Longwave Infrared Camera (LIR) covering 10-μm observes the cloud top temperature on both dayside and nightside. The Lightning and Airglow Camera (LAC) also searches the lightning and airglows on the nightside. And, Radio Science (RS) support those imaging observations by determining the vertical temperature profile and its spatial and temporal variability. With the connection of ground-based support observations and numerical model studies, their large- and meso-scale features of multiple height ranges can provide the information of meridional circulation, mid-latitude jets, and their various wave activities, which provides a link to the vertical and horizontal couplings, the dynamical energy flow maintaining the super-rotation.

After the start of full observations in spring of 2017, Akatsuki started to reveal several unknowns in Venus atmosphere (figure 2). (1) LIR discovered large-scale bow-shaped features in the thermal map at the cloud top of Venus [6]. The feature was first observed on 7 December 2016 and lasted for 4 days. The features do not seem to rotate at the speed of the background atmospheric super-rotation.
(~100 m/s), but seem to be stationary with respect to the ground surface. Comparison with a numerical modeling suggests that those features are manifestations of gravity waves from the ground level.

(2) UVI imaged Venus at two wavelengths: 283 nm in the SO$_2$ absorption band and 365 nm in the band of unknown absorber. Images at these wavelengths were not always well correlated with each other. Investigation of the chemistry and dynamics governing these species is ongoing by utilizing cloud-tracked wind data. (3) IR1 visualized the surface topography of Venus, as imaged at 1.01 μm on the nightside disk. Details of Aphrodite (elevation: 3 to 5 km) were successfully captured. IR1 also

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**Figure 1.** Period of Brightness variations of Venusian OI 135.6 nm observed by Hisaki. The period of solar wind velocity and the dynamic pressure observed by Venus Express is also shown.

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**Figure 2.** Venusian images taken by Akatsuki payloads. (Upper-left) LIR 10-μm image of the full disk. (Upper-right) UVI 283-nm SO$_2$ absorption band image of the dayside taken. (Lower-left) IR1 1.01-μm image of the night-side. (Lower-right) IR2 2.26-μm image of the nightside.
captured small-scale structures in the cloud layer on the dayside, which are clues to the cloud formation process. (4) IR2 acquired 2.26 μm images of night-side disk of Venus, in which waves and turbulences in various scales are visualized. On dayside, 2.02 μm CO₂-absorption band images showed the reflected sunlight image indicates the co-existence of super-rotating cloud features and topography-fixed features. (5) RS obtained vertical profiles of the atmospheric temperature with radio occultation technique. The profiles show significant temporal/spatial variability, the cause of which will be studied by combining RS and camera data. Initial results will be published as the first special issue at the end of 2017. We welcome interests and supports from international scientific community.

3. ERG, Collaborations with ESA (BepiColombo and JUICE), and beyond

As the next mission, we successfully launched the terrestrial inner magnetosphere mission, ERG, on 20 December 2016, and named as Arase (‘a river raging with rough white water’) [7,8]. In January 2017 we finished the initial operations including antenna extensions soon started the investigation of the formation and loss of the terrestrial radiation belt, as a new comer of space weather observatories with the international supports of ground-based observations and numerical modeling study teams.

We designed the international collaborations for further planets than Venus and Mars. Now we are waiting two missions with European scientists. The first is BepiColombo, ESA-JAXA joint mission to Mercury [9]. We provide the Mercury Magnetospherpheric Orbiter (MMO), attached on and transported with the European Mercury Planetary Orbiter (MPO), with hardware contributions to MGF (magnetic field), PWI (plasma waves), MPPE (charged and energetic neutral particles), MDM (dusts), MSASI (sodium exosphere imaging) aboard the MMO and Phobus (UV imaging) aboard the MPO. This project started in early 2000’s, and the MMO spacecraft is already shipped from Japan (JAXA) to Netherlands (ESA). After the launch in 2018 and the long transfer including Venus flyby observations, we will observe the Mercury system from 2025 with two years as multi-spacecraft campaign. The next is the Jupiter ICy Moon Explorer (JUICE), targeting the Jovian system and icy moons with the final orbit around Ganymede. We will directly provide hardware contributions to three teams, GALA (laser altimeter), PEP (charged particles), and RPWI (radio and plasma waves). After the launch in 2022, we will investigate the largest planetary system and icy moons with sub-surface water worlds from 2030.

From 2016, JAXA also started a mission study of a Mars - Phobos sample return mission (the planned launch year: 2024). Using the visible and near infrared spectral imagers for the composition distribution of global and sampling points of Phobos, we are trying to include the capability of the atmospheric continuous monitoring which are done for Venus by Akatsuki. Independently, a piggy-bag-sized Mars mission is also planned in the team led by National Institute of Information and Communications Technology and University of Tokyo. Although those are not yet formal or approved status, the brief introductions and our background strategy for those missions will also be presented.

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