Space Sci Rev (2008) 137: 317–334
DOI 10.1007/s11214-008-9400-x

Lightning Detection by LAC Onboard the Japanese Venus Climate Orbiter, Planet-C

Y. Takahashi · J. Yoshida · Y. Yair · T. Imamura · M. Nakamura

Received: 24 January 2008 / Accepted: 6 June 2008 / Published online: 26 July 2008

Abstract Lightning activity in Venus has been a mystery for a long period, although many studies based on observations both by spacecraft and by ground-based telescope have been carried out. This situation may be attributed to the ambiguity of these evidential measurements. In order to conclude this controversial subject, we are developing a new type of lightning detector, LAC (Lightning and Airglow Camera), which will be onboard Planet-C (Venus Climate Orbiter: VCO). Planet-C will be launched in 2010 by JAXA. To distinguish an optical lightning flash from other pulsing noises, high-speed sampling at 50 kHz for each pixel, that enables us to investigate the time variation of each lightning flash phenomenon, is adopted. On the other hand, spatial resolution is not the first priority. For this purpose we developed a new type of APD (avalanche photo diode) array with a format of 8 × 8. A narrow band interference filter at wavelength of 777.4 nm (OI), which is the expected lightning color based on laboratory discharge experiment, is chosen for lightning measurement. LAC detects lightning flash with an optical intensity of average of Earth's lightning or less at a distance of 3 Rv. In this paper, firstly we describe the background of the Venus lightning study to locate our spacecraft project, and then introduce the mission details.

Keywords Venus · Lightning · Atmosphere · Electricity · Planet-C · VCO · Orbiter · LAC

1 Background of Venus Lightning Study

It is well known to us that lightning on Earth is usually produced by strong convective clouds. According to recent global surveys from ground and spacecraft, the average

Y. Takahashi (✉) · J. Yoshida
Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan
e-mail: spriteselves@gmail.com

Y. Yair
Department of Life and Natural Sciences, The Open University of Israel, Tel Aviv, Israel

T. Imamura · M. Nakamura
Japan Aerospace Exploration Agency, Tokyo, Japan

global occurrence rate of lightning is ∼40 to ∼100 events per second. It is also known that lightning discharges give an impact on the global electric circuit in the atmosphere and the atmospheric chemical processes. Lightning discharges on Earth have several established source mechanisms. Details of the discharge processes can be found in Rakov and Uman (2003). Basically, the discharge requires as its prelude a charging mechanism and a charge separation mechanism to separate opposite polarity charges against their electrical attraction until the developed electric potential difference exceeds the breakdown field of the atmosphere. Terrestrial lightning discharges also occur in volcanic plumes and within dust storms. Recently the cloud to mesosphere/ionosphere discharges such as sprites, elves and blue jets have been discovered successively and these generation mechanisms are investigated with extensive global observations and numerical simulations. Recent planetary exploration missions have revealed that lightning occurs on other planets. On Jupiter, lightning has been detected by optical instruments (Cook et al. 1979; Little et al. 1999; Dyudina et al. 2004) and by the reception of whistlers which appear to be originated from lightning (Gurnett et al. 1979; Lanzerotti et al. 1992). From the results of Galileo and Cassini optical observations, lightning events on Jupiter are found to be associated with storm clouds, and their maximum energy is estimated to be 10^4 times more powerful than that of Earth. The Cassini radio and plasma wave instrument successfully detected many intense impulsive radio signals from Saturn lightning (Gurnett et al. 2005; Fisher et al. 2006).

1.1 Prediction of Venus Lightning

Venus, Earth's sister planet is particularly fascinating, because of its proximity and its permanent obscuring cloud layers. Terrestrial lightning is associated with the generation of electrical charges in convective clouds; hence, there seems a good chance that Venus is also a candidate which has lightning discharge. But the clouds of Venus are mainly composed of sulfuric acid, so it is difficult to induce a charge separation by friction between cryohydrate and hail like Earth. However, depending on the water content of sulfuric acid, there is a possibility that sulfuric acid is in solid state above the middle cloud layer (∼51 km). Furthermore, the fact that the clouds are yellow is due to solid sulfur and ferric chloride existing in clouds. Large upward winds detected by Vega balloons in situ measurements (Sagdeev et al. 1986) suggest good conditions to generate lightning discharges in the Venus atmosphere. Therefore there is high possibility of the existence of lightning on Venus. If lightning exists on Venus, cloud-to-ground discharges would be very difficult to produce at Venus due to the large breakdown voltage of the dense CO_2 atmosphere and the extreme high altitude of the cloud layers above the surface. Hence, intra-cloud discharges are likely to be the most dominant possibility at Venus. Cloud-to-ionosphere lightning events cannot be ruled out at Venus, particularly because the clouds on Venus are 30 to 40 km nearer to the base of the ionosphere than the case of Earth. If there is volcanic activity on Venus, this can become a source of lightning. Considering that Venus has no intrinsic magnetic field, lightning initiated by cosmic rays may be dominant on Venus. Borucki et al. (1996) made laboratory simulations of lightning in the Venus atmosphere (CO_2: 96%, N_2: 4%) and measured the spectral irradiance in the visible range. From the results obtained by observing laser-induced plasmas, it is clear that the observed spectrum is fairly uniform from 360 nm to 760 nm, but shows a very prominent atomic oxygen feature at 777.4 nm. Ohba et al. (2003, 2004) generated discharges in the CO_2 atmosphere and the strongest emission has also been measured at 777.4 nm, atomic oxygen line. Krasnopolsky (2006) pointed out that lightning is only the known source of NO in the lower atmosphere of Venus, and the detection of NO is a convincing and independent proof of lightning on Venus. He derived 5.5 ± 1.5 ppb below 60 km as NO mixing ratio by ground-based telescopic observations, hence concluded that the global flash rate is ∼90 flashes/s and ∼6 km^2/year if a flash energy on Venus is $\sim 10^9$ J.

1.2 Significance of Venus Lightning

Investigation of the Venusian lightning is necessary to progress the following research areas:

Charge separation mechanism: In the generation mechanism of terrestrial lightning, charging and charge separation between cryohydrate and hail are generally considered. However, if Venus lightning is generated in the sulfuric acid clouds, charge separation between droplets is necessary. This will lead to the understanding of sulfuric acid cloud characteristics.

Atmospheric activity: Assuming that Venus lightning is produced by the strong convection like Earth, lightning observation becomes a powerful tool for remote sensing of convective activity in the Venus atmosphere.

Global electric circuit: Earth is considered to be a concentric sphere capacitor surrounded with ground surface and ionosphere, called the global electric circuit. Lightning discharge plays an important role as a generator. From the occurrence rate and the global distribution of Venus lightning, we can estimate the structure of the global electric circuit on Venus.

Chemical effects on atmosphere: Nitric oxides (NOx) production due to lightning discharges is important in the terrestrial troposphere. Particularly, in the equatorial region where lightning discharge occurs most frequently, it is estimated to reach to 40% of the total amount of NOx production. Krasnopolsky (1983b) reported that Venus lightning produces NO and atomic nitrogen. Levine et al. (1982) suggested that at and below cloud level and in the region where solar ultraviolet radiation cannot penetrate, the dissociation of carbon dioxide by lightning may be a significant source of oxygen atoms. For the estimation of the chemical effect of lightning on the Venus atmosphere, it is necessary to investigate the energy characteristics and occurrence rate of lightning.

Volcanic activity: The Magellan spacecraft reported that there is abundant evidence for volcanoes and lava flows on Venus, but current observations have not yet determined whether the planet is geologically alive or dead today. Na et al. (1994) showed a compilation of sulfur dioxide cloud top measurements in Venus and reported that sulfur dioxide has been advanced for the likely rapid increase and observed slow decline. One of these explanations is the existence of active volcanism (Esposito 1984). If lightning is present in Venus and its occurrence region is consistent with volcanoes, we can indirectly view the volcanic activity in Venus. From the above arguments, it is predicted that lightning activities must have an impact on meteorology, atmospheric electricity, and atmospheric chemistry on Venus.

1.3 Past Observations

Venus lightning activity was investigated by optical measurements and electromagnetic wave observations. These are thoroughly reviewed by Russell (1991), Grebowsky et al. (1997), and Russell et al. (2006a, 2006b). Subsequent sections will describe past observations briefly.

1.3.1 Optical measurements

Major past optical measurements of Venus lightning were made as follows.

Venera 9 and 10: In 1975, the Venera 9 grating spectrometer obtained the first optical evidence for lightning on the nightside of Venus at 19h30m local time and 9°S latitude Krasnopolsky (1983a, 1983b). That spectrometer scanned the spectral range from 300 nm to 800 nm in 10 s. Similar observations were made on Venera 10, but no nightside signals were detected. Flashes were only seen over a period of 70 s. There were 10 to 20 flashes per 10 s scan with ∼0.25 s peakwidth—a duration comparable to that of terrestrial flashes. But taking the instrument response time (5 ms) with the sampling time (20 ms) into account, Krasnopolsky (1983a, 1983b) suggested that the flashes consisted of 10 to 20 short duration strokes which occurred at intervals shorter than 20 to 30 ms. Alternative interpretation is that the flashes have a continuous optical emission. Based on the energy measurement of 3×10^7 J and the assumption of constant energy/wavelength between 400 nm and 1100 nm, the power of 7×10^7 J was estimated for the optical energy emitted per flash assuming long duration 14 flashes without substrokes. On the other hand, Krasnopolsky (1983a) estimated that if the flash consisted of 10 to 20 short strokes then the visible stroke energy would drop to 2×10^6 J, corresponding to an estimated $\sim 10^{10}$ J for the total energy dissipated in a single flash.

Pioneer Venus Orbiter: Borucki et al. (1981, 1991) devised a creative use of the Pioneer Venus Orbiter (PVO) Star Tracker to search for optical bursts in the nightside ionosphere of Venus. Scanner measurements near periapsis were studied for 53 orbits in 1988 and 55 orbits in 1990. The cloud coverage consisted of patches predominantly from 2230 local time to the dawn terminator but a patch near the dusk terminator was also viewed. But the rate of pulse detection was compared to the false alarm rate (due to high-energy particles) measured outside of eclipse. Estimated upper bounds to the planetary flash rate were 4×10^7 flashes/km^2/s for terrestrial-like short-duration (few hundred microsecond) flashes at least 50% as terrestrial flash using the 1988 data and 1×10^{-7} flashes/km^2/s for long duration flashes that are at least 1.6% as bright as typical terrestrial flashes using the 1990 data. Despite this study surveying a large area of the nightside of Venus, the total time of search for the two-year 108 orbits study was only 83 s due to very stringent viewing requirements. Nevertheless, this analysis found no evidence of lightning.

Vega 1 and 2 balloons: Vega balloons searched Venus lightning within the cloud layers of Venus in 1985. Sagdeev et al. (1986). Vega 1 and Vega 2 were inserted near midnight local time at 7°N and 7°S latitude, respectively. They floated in the middle cloud layer at altitudes between ∼50 km and ∼54 km. Each carried a silicon PIN diode light detector, sensitive from 400 nm to 1100 nm range, which looked downward with a field of view of ±60 degrees. Both balloons drifted with the wind for 30 hours from midnight through the dawn terminator. No lightning events were detected.

Galileo: In 1990, the Galileo spacecraft flew by Venus on its way to Jupiter. Solid State Imaging (SSI) camera onboard Galileo observed Venus returned 77 useful images from Venus Belton et al. (1991). If Venus lightning flashes have power characteristics and frequency of occurrence similar to those of terrestrial lightning and spectral characteristics similar to those suggested by Borucki et al. (1985), then it is only marginally possible that they could have been detected by the SSI camera. Nevertheless, in view of the considerable interest in Venus lightning, ten frames were devoted to a search. No indications for the presence of lightning flashes were found in these pictures. Roughly estimated upper bound to total optical energy per flash is $\sim 4 \times 10^9$ J.

Ground-based telescope: Hansell et al. (1995) installed the CCD detector at the 153 cm telescope located on Mt. Bigelow, Arizona and searched for light flashes on the nightside of Venus. Their study carefully employed coronagraphic optics, using 2 masks designed in accordance with the specific geometry for each individual night of viewing. An occulting

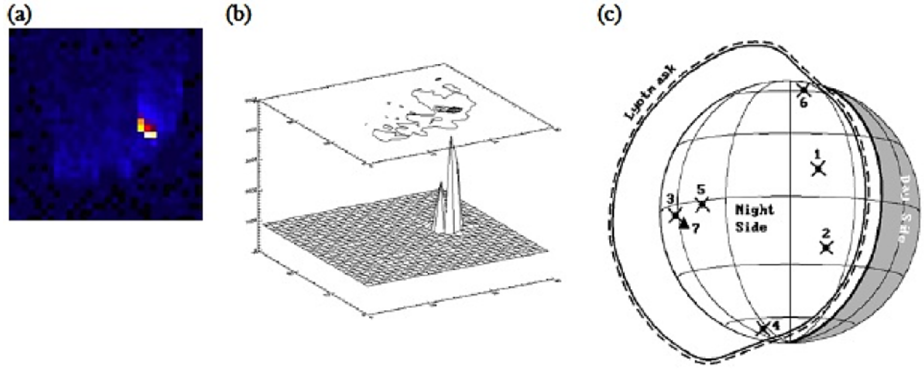

Fig. 1 Example of the CCD image (**a**) and response (**b**) for a flash detected at 777.4 nm from Mt. Bigelow, Arizona, (**c**) Locations of all 7 flash events. Event 7 is the lone burst detected at 658.0 nm and event 1 is the burst depicted in (**b**) (Hansell et al. 1995)

mask was used in the imaging plane and a Lyot mask was used to block diffracted light by the edges and support structure of the secondary mirror. The CCD detector was operated at 18.8 frames/s for 30 pixel Å $\sim$ 30 pixel images of Venus. The observations were made at 777.4 nm (0.7 nm bandwidth) and 656.3 nm (2.0 nm bandwidth). For 8 nights in 1993, the total viewing time was 3 hours at 777.4 nm and 45 minutes at 656.3 nm. The 777.4 nm (atomic oxygen) line is predicted that the strong emission in the Venus lightning spectra by Borucki et al. (1996) and 656.3 nm (Hα) line was selected as a control measurement, such emissions were not initially expected from lightning discharge on Venus. The dusk side of Venus was facing Earth. Seven events met the stringent criteria (including the requirement that an event must be seen on more than one pixel) that the experimenters used for isolating lightning flashes, as shown in Fig. 1. Six events were detected in the 777.4 nm line. The seventh occurred at 656.3 nm. It was then realized that the spectrum of lightning includes a line at 658.0 nm which is within the rather broad pass band of the filter. The 777.4 nm flashes occur at a rate of 2.7×10^{-12} flashes/km^2/s and imply Venus lightning flashes with optical energies from 7×10^7 J to 2×10^9 J.

1.3.2 Electromagnetic Wave Observations

Four electromagnetic wave observations of Venus lightning were made as follows.

Venera 11 and 12 landers: The Venera 11 and 12 probes descended onto Venus in 1978, at similar midday, low latitude locations (Ksanfomality 1980). Each lander carried a high sensitivity loop antenna detector with four narrowband channels centered at 10, 18, 36, and 89 kHz, a wideband signal (8–90 kHz) detector, and an impulse counter. Measurements began at an altitude of $\sim$60 km and continued during the $\sim$1-hour descent and on the surface until contact was lost with the relay spacecraft. Five or six bursts of fine structured wave activity were detected on Venera 11 and two bursts of activity on Venera 12. The duration of the bursts ranged from several to more than 15 minutes. The highest intensities were typically observed in the lowest frequency band centered at 10 kHz. On the surface Venera 12 recorded only one burst of activity 30 minutes after landing, while nothing was recorded from Venera 11. The bursts were composed of pulses occurring at rates ranging from $\sim$10 Hz to $\sim$55 Hz. The pulses seemed to be essentially continuous throughout bursts, with rates that at times exceeded those of radio frequency bursts generated in terrestrial lightning flashes which are typically $\leq$20 Hz.

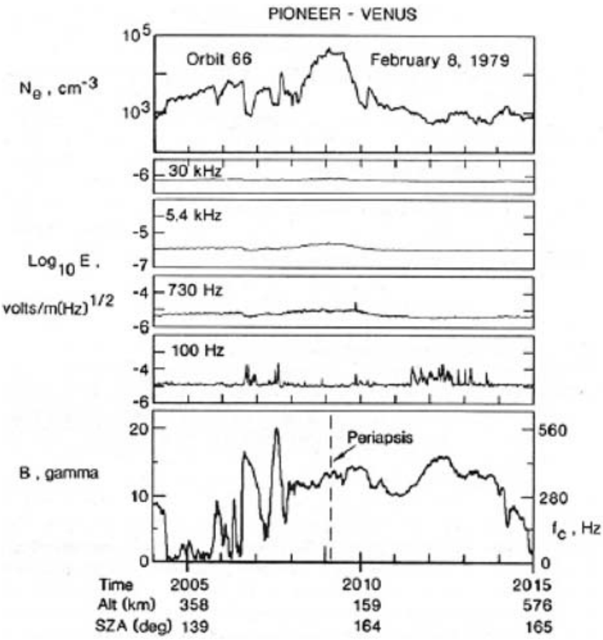

Fig. 2 Intensity of the whistlers associated with discharges in the atmosphere, recorded by the OEFD instrument on the PVO on 8 February 1979 (Ksanfomality 1980). The *vertical scales* give the logarithm of the electromagnetic field intensity, the magnetic field intensity (*bottom*), and the electron density NBeB (*top*). The whistlers were detected in the 100 Hz channel. At the *bottom right* is a gyrofrequency scale

Pioneer Venus Orbiter: PVO carried an electric field detector (OEFD) with four (30% bandwidth) frequency bands centered at 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz (Scarf et al. 1980). Figure 2 shows the recorded bursts of 100-Hz activity in the lower ionosphere on the nightside. Because PVO is situated far above the cloud layers; because *in-situ* plasma processes and atmosphere interactions with the spacecraft can generate electric field waves; because propagation paths from the atmosphere into the ionosphere are not well defined; and because there are anomalous OEFD signals, the OEFD measurements in the lower nightside ionosphere have been the subject of much controversy in the (a) (b) (c) literature for more than a decade. This has led to a labyrinth of pro-and-con lightning publications that has made it difficult for those looking from afar to understand issues. Themes of published papers range from the position that all non-spurious OEFD low-altitude signals have a lightning origin (e.g., Russell 1991) to the opposite position of claiming that any inferred association of the OEFD waves with lightning is pure speculation (e.g., Taylor et al. 1995).

Galileo: During the Galileo's Venus flyby, the plasma wave instrument was used to search for Venus lightning signals from 100-kHz to 5.6-MHz range (Gurnett et al. 1991). The data were acquired for 53 minutes in 1990, at distances of 4 to 5 Rv, where Rv is the Venus radius (6052 km), on the dawn flank from the nightside of Venus. All pulses were isolated and nine pulses were identified. However, from anticipated Venus ionosphere conditions under the solar maximum period of the Galileo flyby, lightning generated radio frequency waves can propagate through the ionosphere only if their frequencies exceed the maximum ionospheric electron plasma frequency ($\sim$1 MHz). So six higher frequency pulses are consistent with a lightning source. A very rough estimate for the flash rate is $\sim 10^{-11}$ flashes/km^2/s assuming 6 valid flash signatures arising from anywhere on the nightside.

Cassini: The Cassini spacecraft, which was on its way to Saturn, made two gravity-assisted flybys of Venus, the first in 1998, and the second in 1999 (Gurnett et al. 2001). During these fly-bys the Radio and Plasma Wave Science (RPWS) instrument conducted a search for impulsive high-frequency (0.125 to 16 MHz) radio signals from lightning.

Such signals have characteristics of terrestrial lightning, and are commonly heard on AM (amplitude-modulated) radios during thunderstorms. Despite the instrument easily detecting signals from terrestrial lightning during a later flyby of Earth (at a global flash rate estimated to be 70 Hz, which is consistent with the rate expected for terrestrial lightning) and many intense impulsive radio signals were successfully detected from Saturn lightning (Gurnett et al. 2005), no similar signals were detected from Venus. If lightning exists in Venus' atmosphere, the results of these observations indicate that it is either extremely rare, or very different from terrestrial lightning.

1.4 Venus Express and Necessary Observation in the Future Mission

As mentioned above, the existence of Venus lightning has been under investigation and still controversial. Nighttime optical signatures have been detected only on the dusk side of midnight. The observations thus far have been too limited to deduce confidently that this reflects a planetary trend. The PVO OEFD broadband signals, concentrated near 21h00m local time, have been hypothesized to be a consequence of lightning discharges but details of the underlying mechanism or alternate plasma-wave sources have yet to be considered. In 2006, Venus Express which carries a magnetometer (MAG) arrived at Venus, and started to sample magnetic wave at 128 Hz (Russell et al. 2006a, 2006b; Zhang et al. 2006b). From preliminary results (Zhang and Russell 2006a), electromagnetic signals which are likely to originate from Venus lightning have been detected.

However, it seems that most scientists think the investigations by an optical instrument is essential for the identification of Venus lightning. Venus Monitoring Camera (VMC) and Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) onboard Venus Express has attempted to detect optical lightning flash on the nightside of Venus. Both of the instruments can positively confirm the existence of terrestrial-strength optical lightning flashes if their frequency in the well-scrutinized southern hemisphere is at least one-tenth of one percent of their frequency on Earth (Baines et al. 2006), but no signals have been observed so far (Markiewicz et al. 2006). With respect to the VMC, one reason may be that it does not have the 777.4 nm filter simulated as the strongest line in the Venus lightning spectra by Borucki et al. (1996). In order to conclusively investigate this phenomenon, it is necessary to build an optical instrument which has both high temporal resolution and high sensitivity to detect the temporal variation within one lightning event. If electromagnetic wave observations ($\sim$100 Hz, $\sim$1–5 MHz) can be made simultaneously, it will be possible to confirm whether or not detected signals are originating from lightning.

2 Japanese Venus Climate Orbiter Mission: Planet-C

2.1 Scientific Objectives and Instruments

The Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), will launch a Venus Climate Orbiter (VCO) in 2010. This mission, which is called Planet-C, is the third planetary mission in Japan and aims at understanding the meteorology and climate of the Venus atmosphere. This Japanese Venus mission was formally proposed in January 2001 by the Venus exploration working group with members from various universities and institutes. This proposal was approved as one of the M-V satellite projects by the space science committee of ISAS in May 2001, and the mission was named Planet-C. The code name Planet-C means the third Japanese planetary explo-

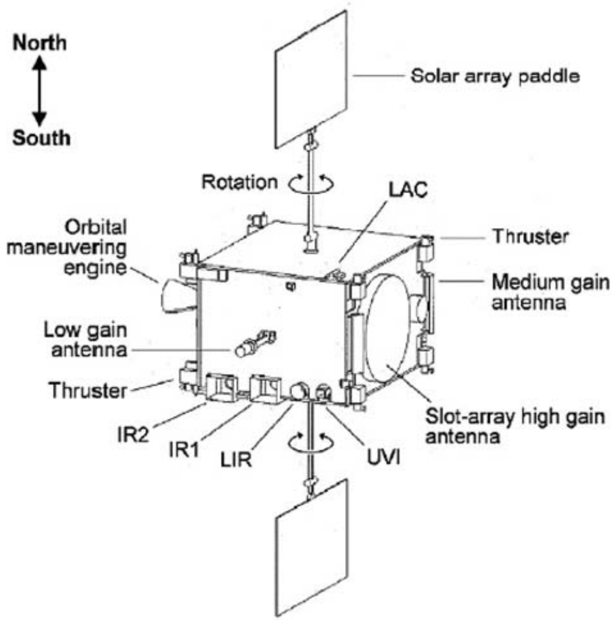

Fig. 3 Configuration of VCO (Nakamura et al. 2007)

ration mission; Planet-A mission to Halley's comet and Planet-B mission to Mars which were named *Sakigake* and *Nozomi*, respectively, after their successful launching. In August 2006, the launching vehicle was changed from M-V to H-IIA. The details of this mission are summarized in Japanese Venus Mission Proposal (2001), Ishii et al. (2004), and Nakamura et al. (2007). The VCO is the first meteorological satellite of a Venus orbiter. The science goals are as follows:

1) To understand the mechanism of the superrotation of the atmosphere
2) To understand the structure of meridional atmospheric circulation
3) To survey the global structure of the meso-scale meteorological phenomena
4) To understand the mechanism of cloud formation and lightning discharge
5) To measure the ground surface radiant emittance and exploration of active volcanoes.

In order to achieve these objectives, five cameras have been developed. These cameras cover the wavelength range of UV (280 and 360 nm), near-IR (1.0, 1.7, 2.0, and 2.3 μm), and long-IR (8–12 μm). The lightning and airglow camera (LAC) measures lightning flashes and airglow emissions on the Venus nightside disk. The Near-IR cameras (IR1 and IR2) measure lower clouds around 50 km altitude and the distribution of carbon monoxide below clouds, while the ultraviolet imager (UVI) and the longwave-IR camera (LIR) measure the cloud top region around 70 km. Multi-wavelength images obtained from concurrent operation of these cameras and the temperature profiles obtained from radio occultation enable us to investigate the three-dimensional structures of atmosphere and their dynamics.

2.2 Spacecraft Design

The specifications of the spacecraft are summarized in Table 1. The VCO will be launched by H-IIA in the early 2010 and arrival at Venus is scheduled for late 2010. The configuration of the spacecraft is illustrated in Fig. 3. The spacecraft has a three-axis stabilized attitude

Table 1 Specifications of the spacecraft

Parameters	Value
Launch	Early 2010
Arrival	Late 2010
Vehicle	H-IIA
Launch site	Tanegashima Space Center (TNSC), Japan
Orbital insertion	Direct insertion (into interplanetary orbit by a rocket)
Orbital period	~180 days (till Venus arrival)
Observation period	More than 2 years (after Venus arrival)
	Periapsis: ~300 km
	Quasi-synchronous equatorial orbit
Orbit	Apoapsis: ~78700 km (13 Rv*)
	Period: 30 hours
	Inclination: ~172°
	B-Plane angle: ~185°
Shadow duration	Umbra: 90 minutes (including penumbra: 100 minutes)
Size	1450 × 1040 × 1400 mm
	Wet: 500 kg
Mass	Dry: 313 kg
	Science payload: 32.50 kg
Attitude control	3-axis stabilized

*Rv: Venus radii (= ~6050 km)

control to give the optimum platform for atmospheric imaging. This orbit allows the angular motion of the spacecraft to be approximately synchronized with the westward mean zonal wind over a span of 24 hours around the apogee region. This geometry enables us to observe temporal evolution of meteorological phenomena. Such 20-hour continuous observations are performed in every orbital revolution over the mission life of more than 2 years. The time scales of atmospheric phenomena recorded in such datasets range from several minutes to several months. The synchronized orbit also allows derivation of the horizontal wind fields from cloud motions with high accuracy. Close-up images of meso-scale features and limb images are obtained near the periapsis. The shadow region along the orbit is utilized for observing lightning flashes and airglow. Radio occultation experiment is performed when the spacecraft is hidden by Venus as viewed from the ground station.

2.3 Lightning and Airglow Camera: LAC

The lightning and airglow camera (LAC), one of the five cameras installed in VCO, has been developed by our team of the Planetary Atmosphere Physics Laboratory, Department of Geophysics, Graduate School of Science, Tohoku University. LAC is a new camera developed for measurements of planetary lightning flashes and global distributions of airglow. The LAC measures Venus lightning flashes and airglows on the nightside disk when the VCO is located within the umbra (shadow region) of Venus. As described in Sect. 1, the existence of Venus lightning is still a controversial issue in spite of optical and electromagnetic wave observations for more than 25 years. We aim to conclude this controversy by LAC observations. The high speed optical detector of the LAC is adopted for optical measurement, which enables us to distinguish between lightning flashes and electrical noise pulses. The scientific objectives of the LAC are as follows:

1) To confirm, for the first time, the existence of Venus lightning
2) To obtain information on the durations on flashes, optical flash energies, spatio-temporal distributions, and the global occurrence rates
3) To detect volcanic thunderstorms in corporation with near-IR camera 1 (IR1)
   Furthermore, using the above observation data, the following subjects are investigated:
4) To confirm vertical convection in Venus' atmosphere
5) To obtain part of the fundamental information relating to the global electric circuit of the atmosphere
6) To evaluate the chemical impact of lightning on the Venus atmosphere
7) To explore the relationship between active volcanoes and lightning In addition, the LAC has enough sensitivity to detect airglow emissions in the Venus upper atmosphere. The science goals of LAC airglow observations are listed as follows:
8) To investigate the global distributions and the spatio-temporal variations of molecular and atomic oxygen airglows
9) To detect the wavelike structures caused by atmospheric gravity waves
10) To investigate the vertical profiles of airglow intensities

Furthermore, using the above observation data, the following subjects are investigated:

11) To understand the structures and spatio-temporal variations of global circulation in the upper atmosphere
12) To investigate the coupling process between the upper atmosphere and the lower atmosphere by evaluating the effect of atmospheric gravity waves
13) To understand the atomic oxygen emission mechanism

3 Development of LAC

3.1 Required Performances

We have designed and developed the LAC, carrying out various examinations and experiments since FY 2001. As summarized in Table 2, the LAC has been developed in collaboration with several institutes and corporations.

Table 2

Department	Person or company in charge
Principal investigator	Yukihiro Takahashi (Tohoku University)
Co-investigators	Masaki Tsutsumi (National Institute of Polar Research) Tomoo Ushio (Osaka University)
Electronics and assembly	Meisei Electric Co., Ltd.
Optical system and lenses	Nikon Corporation
Optical sensor	Hamamatsu Photonics K. K.
Filters	Barr Associates, Inc. (Fujitok Corporation)
Satellite system	NEC TOSHIBA Space Systems, Ltd.

In order to achieve scientific objectives as shown in previous section, we set the sensitivity requirement that we can detect the same intensity of typical terrestrial lightning flashes from an altitude of 5 Rv even if they occur under the cloud layer. The optical energies of Venus lightning flashes have been estimated to be $\sim 10^7$ to $\sim 10^9$ J (Krasnopolsky 1983a; Hansell et al. 1995), which are ~ 10 to $\sim 10^3$ times more than those of typical terrestrial lightning flashes ($\sim 10^6$ J). However, weaker flashes may not be detected because of the low sensitivity and low temporal resolution of the instrument. If the above requirement can be satisfied, this instrument allows us to detect 1/1000 intensity of typical terrestrial lightning flash from an altitude of 1000 km. In this study, the required Signal-to-Noise Ratio (SNR) to detect lightning flash is set to be 10.

In order to detect the Venus lightning and airglow with a single camera, the following requirements have to be satisfied.

1) To adopt a high-speed and high-sensitivity optical sensor: Although the duration of the Venus lightning flash is unknown, it is expected to be extremely short similar to the case of terrestrial lightning. The intensities of Venus airglow, are expected especially atomic oxygen lines, are expected to be very weak. Therefore, the LAC needs a high-speed and high-sensitivity sensor.
2) To detect a lightning flash using pre-trigger sampling: Since the LAC aims to detect temporal evolution in lightning flashes, a high-speed sampling is essential. Since continuous high-speed data sampling is impossible for planetary missions, it is necessary to adopt a pre-trigger sampling method which enables us to save only the pre- and post- trigger data with high sampling rates.

3.2 Design of LAC

We started the design of the LAC in FY2001. The final optical performances of LAC are summarized in Table 3.

3.3 Observing Wavelengths

We selected interference filters for LAC as follows: Lightning observation is made of wavelength at 777.4 nm (atomic oxygen line). The laboratory simulations by Borucki et al. (1996) that this line is the strongest emission in the Venus lightning spectrum. In addition, Hansell et al. (1995) presented evidence on the Venus lightning flashes in the nightside disk at this wavelength. Airglow observation is performed in the wavelength range of 480–605 nm (molecular oxygen Herzberg II band), 557.7 nm (atomic oxygen green line). The Herzberg II band is the strongest emission in the visible wavelength range of Venus airglow (Krasnopolsky 1983a). The atomic oxygen green line emission was discovered by recent ground-based observations (Slanger et al. 2001), while the Venera 9 and 10 orbiters reported the lack of this emission (Krasnopolsky 1983a). In addition, in order to record background, airglow-free images are acquired at 545.0 nm.

3.4 APD Detector

We adopt a multi-anode silicon avalanche photodiode (SiAPD) as a detector. The APD is an opto-semiconductor and high-speed, high-sensitivity photodiode utilizing an internal gain mechanism that functions by applying a reverse voltage. The APD gain (M; multiplication ratio) depends on the electric field applied across the avalanche layer. Normally, the higher

Table 3 Optical performances of LAC

Parameter	Value
Wavelengths	777.4 nm (lightning)
	480-605 nm (O_2 Herzberg II band airglow)
	557.7 nm (O_2 line airglow)
	545.0 nm (airglow-free background image)
Interference filter	Array bandpass filter
Image sensor	Hamamatsu Si APD (Avalanche photodiode) 4461
Pixel size	2.0 mm × 2.0 mm
	Gap between pixels: 0.20 mm
Image sensor format	8 pixels × 8 pixels
Field of view	16.0 degrees × 16 degrees
	($2\omega = 23.3$ degrees)
Angular resolution	1 .84 degrees/pixel
Spatial resolution	32 km @1,000 km
	580 km @3Rv
Optics	Image-side telecentric
Objective lens	Aspheric lens
Entrance pupil (diaphragm)	25.0 mm dia
Focal length (F number)	61.9 mm ($F/{\sim}2.5$)

the reverse voltage (VR) becomes, the higher the gain becomes. APDs have excellent vibration and thermal tolerances so that they are suitable for space application. However, the APD gain also has time-dependent characteristics. The gain at a certain reverse voltage becomes small as the temperature rises. Therefore, in order to obtain constant output, it is necessary to adjust the reverse voltage according to the changes in temperature or to keep the APD temperature constant. We developed a new multi anode SiAPD (No. 4461) in collaboration with Hamamatsu Photonics. The design and the view are displayed in Fig. 4. It has 8 by 8 matrix of 2 mm square pixels and the gap between pixels is 0.2 mm. The maximum gain is designed to be 100.

3.5 Array Bandpass Filter

Imaging observations of LAC are made using five filters. A filter wheel system is usually adopted to choose one of filters. However, this system is very heavy (∼1.5 kg) and there is risk of an electric motor's breaking down. Instead of the filter wheel system, we have developed the rectangular interference filters in corporation with Barr Associates Inc. and Fujitok Corporation. Measurement of lightning flash at 777.4 nm is carried out with 4 × 8 pixels, while measurements of airglow emissions at 551.0–552.5 nm, 557.7 nm, and 630 nm are performed with 1 by 8 pixels, respectively. Airglow-free background images are also acquired at 545.0 nm with 1 × 8 pixels with the same kind of filter. As illustrated in Fig. 5, a complex of these interference filters, which is called as an array bandpass filter (ABPF), is placed on the detector. Each rectangular filter is bonded with black epoxy. Support glass is placed on both side of ABPF to stabilize its structure. In order to improve its vibrational tolerance, it is surrounded with a super invar case made by Nikon Corporation.

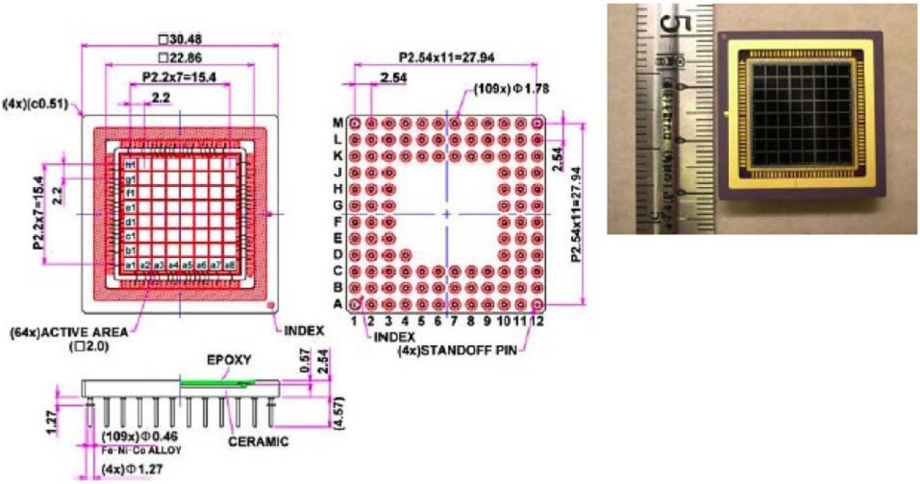

Fig. 4 Design (*left*) and view (*right*) of SiAPD 4461

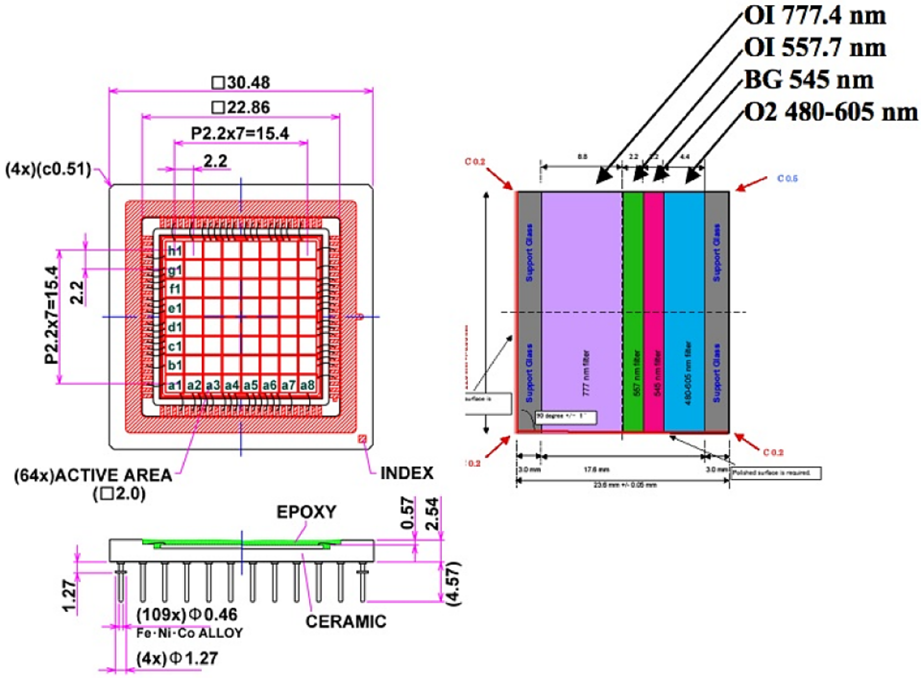

Fig. 5 Schematic view of array bandpass filter

3.6 Optical Design

The LAC is operated when the VCO spacecraft is located within the umbra (shadow region) of Venus. FOV is set to be 16 × 16 degrees so that it can cover the whole nightside disk using all of the SiAPD pixels when VCO is located at ∼5 Rv. Although the half angle corresponding to the image circle (ω) is 11.3 degrees based on paraxial theory, it becomes 11.6 degrees taking the distortion into consideration. Angular resolution per pixel is 1.84 degrees/pixel because of the pixel size and the gap between pixels. Based on the sizes of Si APD and FOV, the focal length of this optics is calculated to be 61.9 mm. The aperture is set as 25.0 mm taking the mass and the size of LAC into consideration. All of the ABPF (interference filters) of the LAC have narrow (or broad) bandwidths (a few nanometers min.); therefore, we have to consider their central wavelength shift as a function of incident angle. We adopted an image-side telecentric system as the optics of LAC. Using this optical design the chief rays become parallel to the optical axis on the image side. This realizes that the maximum incident angle become 11.4 degrees, which is much smaller than that of the non-telecentric system.

The LAC optics is bright (F number is ∼2.5) by adopting a single aspherical lens to save the mass. The material of the lens is quartz, which has excellent radiation tolerance. The focal length depends on wavelength because chromatic aberration is not considered. According to a spot diagram analyzed by Nikon Corporation, spot size in shorter wavelength range is smaller at object-side defocus position due to axial chromatic aberration. In addition, spot size formed by luminous flux with a large angle of view is smaller at object-side defocus position due to field curvature. We decided an arrangement of ABPF as shown in Fig. 5. In order to stabilize the structure of ABPF, rectangular filters covering 1×8 pixels are placed on the both sides.

The LAC has the structure without filter wheels to satisfy the mass requirement; thus there are no shutters in the LAC optics. According to the orbital analysis by NEC TOSHIBA Space Systems, Ltd., it is reported that direct sunlight illuminates the first component of the optics every orbital revolution, although observations are carried out only when the orbiter is located in the Venus umbra. Normally, power supply is turned off except for observation time; however, extreme amount of light and thermal radiation may cause APD's or ABPF's to break down. In order to reduce light and thermal radiation influx as much as possible, an interference filter which transmits only observing wavelength range is set on the front of LAC optics. Here this filter is called a Solar Blocking Filter (SBF). Reflecting light from the detector and SBF may produce unegligible ghost image. Considering half angle of view with margin, the SBF is inclined 9 degrees relative to principle plane so that ghost image cannot be formed at the receiving side of the detector.

3.7 Observation Plan and SNR Estimation

In order to measure the luminous phenomena which show different temporal variations (lightning flashes and airglow emissions), current to voltage conversion amplifiers with high-speed and low-speed time constant are connected to APD's pixels. Note that there are no plans to observe lightning and airglow simultaneously. The planned observation modes are summarized in Table 4 and described here for only lighting observation mode.

Assuming that duration of Venus lightning flashes is the same as that of representative terrestrial ones (∼20 micro sec), sampling frequency is set to be 50 kHz. This enables us to detect the temporal variations of brightness within one flash so that we can distinguish between lightning flash and electrical noise pulse. However, high temporal sampling produces a large amount of data. We adopt the pre-trigger sampling method, which can acquire 2–2000 ms data from pre- to post-trigger periods depending on the duration of lightning flashes. Estimated SNR of lightning observations as a function of optical energy and distance from light source is shown in Fig. 6. From an altitude of 5 Rv, the LAC enables us to detect the same intensity of typical terrestrial lightning flash (106 J) with SNR of ∼12.

Table 4 Observation modes

Parameter	Lightning observation mode	Airglow observation mode
Method	Pre-trigger sampling	Numerical integration
Temporal resolution (Sampling rate)	5×10^4 samples/s/pixel	1 sample/integration time/pixel
Data acquisition time	2, 20, and 200 ms (Sum of pre- and post-trigger time period)	–
Integration time	–	10, 30, and 90 s
Data depth	8 bit/pixel	24 bit/pixel

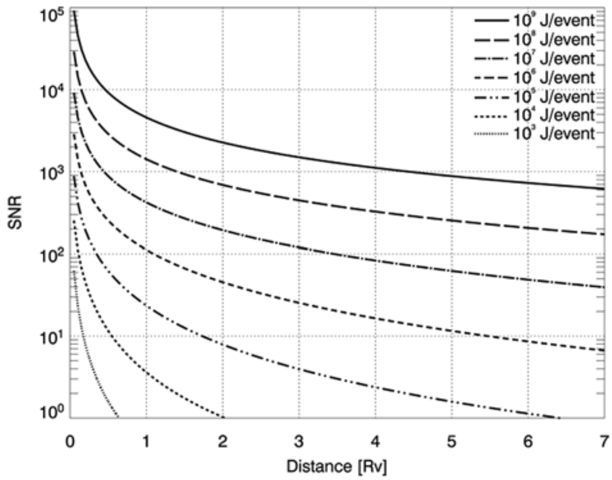

Fig. 6 Estimated SNR of lightning observations as a function of optical energy and distance from light source. From an altitude of 5 Rv, LAC enables us to detect the same intensity of typical terrestrial lightning flash (106 J) with SNR of ∼12

3.8 Proto Model Design

Based on the considerations above a prototype LAC model has been produced. The LAC consists of the sensor (LAC-S) and the electronics (LAC-E). The former includes optics, detector, current-to-voltage conversion amplifiers, Bright Object Sensor (BOS), thermal sensor, high voltage power supply, etc., while the latter includes power supply, followers, Analog-to-Digital Converters (ADCs), multiplexers (MPXs), Field Programmable Gate Array (FPGA), Static Random Access Memories (SRAMs), DC-to-DC converters, etc. 3-dimensional images of LAC-S and LAC-E and the detailed cross section of LAC-S are depicted in Fig. 7. On the assumption that sunlight or reflected sunlight from the Venus dayside disk illuminates the LAC due to some troubles of orbital operation while LAC observes the Venus nightside disk, the bright object sensor (BOS) is placed on the top of LAC-S to protect the APD. The BOS enables us to lower the high voltage and to turn off the power supply before the LAC detects a large amount of light. Configuration of VCO is depicted in Fig. 3. LAC will be set on the $+Y$ panel and view direction look toward $-X$-axis, which is the same view direction of other cameras.

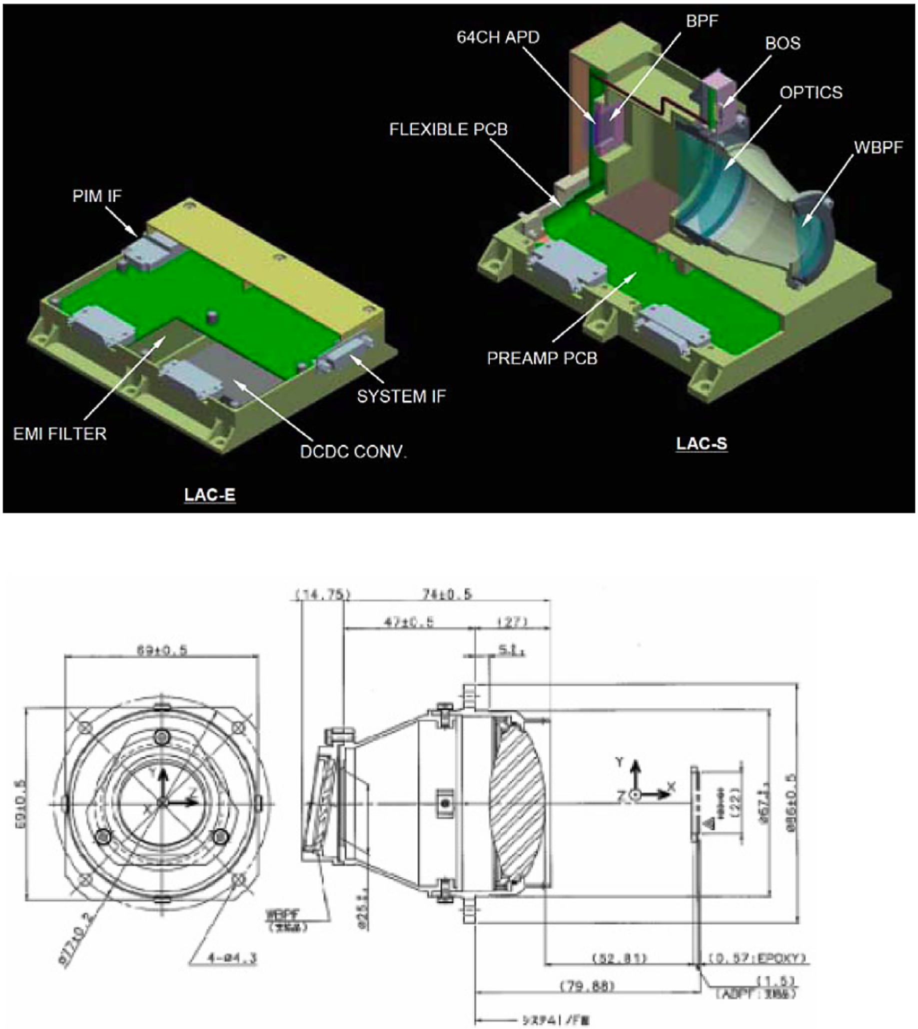

Fig. 7 (*Top*) 3-dimensional images of LAC-S and LAC-E and (*bottom*) cross section of LAC-S

4 Summary and Conclusion

LAC is a high-speed imaging sensor which measures lightning flashes and airglow emissions on the nightside disk of Venus from within the umbra (shadow region). One of the major goals of LAC is to settle controversy on the occurrence of lightning in the Venusian atmosphere. Lightning observations will give us information on the charging mechanism, charge separation mechanism, physics of sulfuric acid clouds, mesoscale meteorology and its impacts on atmospheric chemical processes. If lightning discharge occurs in the upwelling cloud regions like as the Earth and Jupiter, we can monitor vertical convections inside the cloud layer via lightning detection. The 777.4 nm [OI] line associated with the excitation of atomic oxygen is expected to be a strong emission from the laboratory discharge experiment in a simulated Venusian atmosphere (Borucki et al. 1996). Possible lightning flashes were detected on the nightside disk of Venus at this wavelength by a ground-based telescope (Hansell et al. 1995). But, due to the observational difficulties, the existence of lightning in Venus' atmosphere remains controversial.

LAC is designed to detect lightning flashes with an intensity of 1/100 of standard lightning on the Earth when viewed from 1000 km altitude. LAC has a field-of-view of 16 degrees, and the detector uses a multi-anode avalanche photo-diode (APD) that has 8×8 matrix of 2-mm square pixels. We will measure lightning flashes at 777.4 nm [OI] with 4×8 pixel area. A complex of these interference filters is placed on the detector. Individual lightning flash events are sampled at 50-kHz by pre-triggering. The field-of-view of one pixel corresponds to about 35 km on the Venusian surface at 1000 km altitude and 850 km at 3 Rv altitude. LAC onboard VCO will arrive at Venus in 2010 and could conclude controversial situation on lightning activity.

Acknowledgements We would like to acknowledge all members of the VCO project team for developing the mission plan and the spacecraft and instrument designs. The LAC has been developed, collaborating with the Meisei Electric Co., Ltd., Hamamastu, Photonics K. K., Nikon Corp., and Barr Associates, Inc./Fujitoku Corp.

References

K.H. Baines, S. Atreya, R.W. Carlson, D. Crisp, P. Drossart, V. Formisano et al., To the depths of Venus: Exploring the deep atmosphere and surface of our sister world with Venus Express. Planet. Space Sci. **54**, 1263–1278 (2006). doi:10.1016/j.pss.2006.04.034

M.J.S. Belton, P.J. Gierasch, M.D. Smith, P. Helfenstein, P.J. Schinder, J.B. Pollack et al., Images from Galileo of the Venus cloud deck. Science **253**, 1531–1536 (1991). doi:10.1126/science.253.5027.1531 Medline

W.J. Borucki, J.W. Dyer, G.Z. Thomas, J.C. Jordan, D.A. Comstock, Optical search for lightning on Venus. Geophys. Res. Lett. **8**, 233–236 (1981). doi:10.1029/GL008i003p00233

W.J. Borucki, R.L. Mc Kenze, C.P. McKay, N.D. Duong, D.S. Boac, Spectra of simulated lightning on Venus, Jupiter, and Titan. Icarus **64**, 221–232 (1985). doi:10.1016/0019-1035(85)90087-9 Medline

W.J. Borucki, J.W. Dyer, J.R. Phillips, P. Phan, Pioneer Venus Orbiter search for Venusian lightning. J. Geophys. Res. **96**, 11033–11043 (1991). doi:10.1029/91JA01097

W.J. Borucki, C.P. McKay, D. Jebens, H.S. Lakkaraju, C.T. Vanajakshi, Spectral irradiance measurements of simulated lightning in planetary atmospheres. Icarus **123**, 336–344 (1996). doi:10.1006/icar.1996.0162

A.F. Cook, T.C. Duxbury, G.E. Hunt, First results on Jovian lightning. Nature **280**, 794 (1979). doi:10.1038/280794a0

U.A. Dyudina, A.D. Del Genio, A.P. Ingersoll, C.C. Porco, R.A. West, A.R. Vasavada et al., Lightning on Jupiter observed in the Hα line by the Cassini imaging science subsystem. Icarus **172**, 24–36 (2004). doi:10.1016/j.icarus.2004.07.014

L.W. Esposito, Sulfur dioxide—Episodic injection shows evidence for active Venus volcanism. Science **223**, 1072–1074 (1984). doi:10.1126/science.223.4640.1072 Medline

G. Fisher, M.D. Desch, P. Zarka, M.L. Kaiser, D.A. Gurnett, W.S. Kurth, W. Macher, H.O. Rucker, A. Lecacheux, W.M. Farrell, B. Cecconi, Saturn lightning recorded by Cassini/RPWS in 2004. Icarus **183**, 135–152 (2006). doi:10.1016/j.icarus.2006.02.010

J.M. Grebowsky, R.J. Strangeway, D.M. Hunten, Evidence for Venus lightning, in *Venus II*, ed. by S.W. Bougher et al. (Univ. of Arizona Press, Tucson, 1997), pp. 125–157

D.A. Gurnett, R.R. Shaw, R.R. Anderson, W.S. Kurth, F.L. Scarf, Whistlers observed by Voyager 1: Detection of lightning on Jupiter. Geophys. Res. Lett. **6**, 511–514 (1979). doi:10.1029/GL006i006p00511

D.A. Gurnett, W.S. Kurith, A. Roux, R. Gendrin, C.F. Kennel, S.J. Bolton, Lightning and plasma wave observations from the Galileo flyby of Venus. Science **253**, 1522–1525 (1991). doi:10.1126/science.253.5027.1522 Medline

D.A. Gurnett, P. Zarka, R. Manning, W.S. Kurth, G.B. Hospodarsky, T.F. Averkamp et al., Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning. Nature **409**, 313–315 (2001). doi:10.1038/35053009 Medline

D.A. Gurnett, W.S. Kurth, G.B. Hospodarsky, A.M. Persoon, T.F. Averkamp, B. Cecconi et al., Radio and plasma wave observations at Saturn from Cassini's approach and first orbit. Science **307**, 1255–1259 (2005). doi:10.1126/science.1105356 Medline

S.A. Hansell, W.K. Wells, D.M. Hunten, Optical detection of lightning on Venus. Icarus **117**, 345–351 (1995). doi:10.1006/icar.1995.1160

N. Ishii, H. Yamanaka, S. Sawai, M. Shida, T. Hashimoto, M. Nakamura et al., Current status of the PLANET-C Venus orbiter design. Adv. Space Res. **34**, 1668–1672 (2004). doi:10.1016/j.asr.2004.07.006

V.A. Krasnopolsky, Venus spectroscopy in the 3000–8000 Å region by Veneras 9 and 10, in *Venus*, ed. by D.M. Hunten et al. (Univ. of Arizona Press, Tucson, 1983a), pp. 459–483

V.A. Krasnopolsky, Lightnings and nitric oxide on Venus. Planet. Space Sci. **31**, 1363–1369 (1983b). doi:10.1016/0032-0633(83)90072-7

V.A. Krasnopolsky, A sensitive search for nitric oxide in the lower atmospheres of Venus and Mars: Detection on Venus and upper limit for Mars. Icarus **182**, 80–91 (2006). doi:10.1016/j.icarus.2005.12.003

L.V. Ksanfomality, Discovery of frequent lightning discharges in clouds on Venus. Science **284**, 244–246 (1980)

L.J. Lanzerotti, K. Rinnert, G. Dehmel, F.O. Gliem, E.P. Krider, M.A. Uman et al., The Lightning and Radio Emission Detector (LRD) instrument. Space Sci. Rev. **60**, 91–109 (1992). doi:10.1007/BF00216851

J.S. Levine, G.L. Gregory, G.A. Harvey, W.E. Howell, W.J. Borucki, R.E. Orville, Production of nitric oxide by lightning on Venus. Geophys. Res. Lett. **9**, 893–896 (1982). doi:10.1029/GL009i008p00893

B. Little, C.D. Anger, A.P. Ingersoll, A.R. Vasavada, D.A. Senske, H.H. Breneman et al., The Galileo SSI Team, Galileo images of lightning on Jupiter. Icarus **142**, 306–323 (1999). doi:10.1006/icar.1999.6195

W.J. Markiewicz, D.V. Titov, N. Ignatiev, H.U. Keller, D. Crisp, L. Esposito et al., First results from Venus Monitoring Camera on Venus Express, American Astronomical Society, the 38th DPS meeting, Pasadena, US, 2006

C.Y. Na, L.W. Esposito, W.E. McClintock, C.A. Barth, Sulfur dioxide in the atmosphere of Venus: II Modeling results. Icarus **112**, 389–395 (1994). doi:10.1006/icar.1994.1193

M. Nakamura, T. Imamura, M. Ueno, N. Iwagami, T. Satoh, S. Watanabe, et al., PLANET-C: Venus climate orbiter mission of Japan. Planet. Space Sci. **55**, 1831–1842 (2007).

Y. Ohba, H. Itabashi, Y. Goto, Optical measurements in long gap carbon dioxide discharge, Proc. Soc. Atmos. Electr. Jpn. **63** (2003) (in Japanese)

Y. Ohba, H. Koriyama, Y. Sato, Y. Goto, Spectral measurements of long gap carbon dioxide discharge by 1 MVIG, Proc. Soc. Atmos. Electr. Jpn. **64** (2004) (in Japanese)

V.A. Rakov, M.A. Uman, *Lightning: Physics and Effects* (Cambridge Univ. Press, Cambridge, 2003)

C.T. Russell, Venus lightning. Space Sci. Rev. **55**, 317–356 (1991)

C.T. Russell, T.L. Zhang, M. Delva, W. Magnes, R.J. Strangeway, H.Y. Wei, Lightning on Venus inferred from whistlemode waves in the ionosphere. Nature **450**, (2006a). doi:10.1038/nature05930

C.T. Russell, R.J. Strangeway, T.L. Zhang, Lightning detection on the Venus Express mission. Planet. Space Sci. **54**, 1344–1351 (2006b). doi:10.1016/j.pss.2006.04.026

R.V. Sagdeev, V.M. Linkin, V.V. Kerzhanovich, A.N. Lipatov, A.A. Shurupov, J.E. Blamont et al., Overview of VEGA balloon in situ meteorological measurements. Science **231**, 1411–1414 (1986). doi:10.1126/science.231.4744.1411 Medline

F.L. Scarf, W.W.L. Taylor, C.T. Russell, L.H. Brace, Lightning on Venus: Orbiter detection of whistler signals. J. Geophys. Res. **85**, 8158–8166 (1980). doi:10.1029/JA085iA13p08158

T.G. Slanger, P.C. Cosby, D.L. Huestis, T.A. Bida, Discovery of the atomic oxygen green line in the Venus night airglow. Science **291**, 463–465 (2001)

H.A. Taylor Jr., L. Kramer, P.A. Cloutier, S.S. Walker, Signatures of solar wind interaction with the nightside of Venus. Earth Moon Planets **69**, 173–199 (1995). doi:10.1007/BF00613097

Venus exploration working group, Japanese Venus Mission Proposal. The Institute of Space and Astronautical Science, 2001

T.L. Zhang, C.T. Russell, Magnetometer team, Solar wind interaction with Venus: Venus Express magnetic experiment initial results, American Astronomical Society, the 38th DPS meeting, Pasadena, US, 2006a

T.L. Zhang, W. Baumjohann, M. Delva, H.-U. Auster, A. Balogh, C.T. Russell et al., Magnetic field investigation of the Venus plasma environment: Expected new results from Venus Express. Planet. Space Sci. **54**, 1336–1343 (2006b). doi:10.1016/j.pss.2006.04.018