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Updated Review of Planetary Atmospheric Electricity

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Abstract This paper reviews the progress achieved in planetary atmospheric electricity, with focus on lightning observations by present operational spacecraft, aiming to fill the hiatus from the latest review published by Desch et al. (Rep. Prog. Phys. 65:955–997, 2002). The information is organized according to solid surface bodies (Earth, Venus, Mars and Titan) and gaseous planets (Jupiter, Saturn, Uranus and Neptune), and each section presents the latest results from space-based and ground-based observations as well as laboratory experiments. Finally, we review planned future space missions to Earth and other planets that will address some of the existing gaps in our knowledge.

Keywords Lightning · Thunder · Radio emissions · Whistlers · Transient luminous events · Charging processes · SED—Saturn Electrostatic Discharges · Optical emissions · Dust · Dust devils · Triboelectric charging · Ionosphere · Spectrum · Cassini · Voyager · Mars Express · Venus Express · Remote sensing · Flash rate · Terrestrial gamma-ray flashes · Satellite · Mars · Venus · Jupiter · Titan · Saturn · Uranus · Neptune · Pioneer Venus Orbiter · Galileo · Electric field · Conductivity · Schumann resonance · Optical efficiency · Hydrocarbon · Cloud

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1 Introduction

There is now numerous evidence of lightning activity in atmospheres of the planets of our solar system. The most unequivocal and strong observations are optical emissions detected by cameras of orbiting or flying-by spacecraft. The intense lightning light is caused by the heating of the discharge channel, which emits continuum and line spectra that are observed directly as scattered light by clouds (on Earth, Jupiter; controversial for Venus). Lightning can also be observed indirectly by measurements of transient luminous events (TLE) caused by them in the region above the cloud layers (Earth). In addition, indirect electromagnetic evidence for lightning activity is provided by whistlers propagating along magnetic field-lines penetrating the ionosphere, high frequency (HF) and very high frequency (VHF) emissions above the ionospheric cut-off frequency (discussed by Zarka et al. (2008) in this issue), low-frequency radio emission by the current channel acting as an antenna in a broad spectrum peaking (at Earth) at ∼1–10 kHz (decreasing as f^{-1} to f^{-2} at higher frequencies) and finally by detecting the signature of Schumann Resonances at extremely low frequencies ($<$ a few tens of Hz), which are trapped in the surface-ionosphere cavity. The major properties of the ionospheres of various planets are summarized in Table 1. Spectroscopic observations by ground-based telescopes or orbiting spacecraft offer chemical evidence of lightning by identifying non-equilibrium concentrations of certain compounds and the presence of exotic species, which cannot be explained by other phenomena. Indeed, the prediction that lightning takes place in other planetary atmospheres dates back to the mid-1970s, when data on the chemistry and meteorology of different planets was obtained from spacecraft and ground-based spectroscopy (e.g. Bar-Nun 1975, 1979). The importance of lightning as an agent for chemical reactions in pre-biotic circumstances was recognized even earlier, in the famous Urey–Miller experiments (Miller 1953), where electrical sparks were

Table 1 Characteristics of planetary ionospheres

Body	Characteristic	Reference
Venus	Ionospheric layer peak at ∼140 km / electron density $\sim 4 \cdot 10^5$ cm^{-3}	Knudsen et al. (1987)
Mars	Ionospheric layer peak at ∼120 km / electron density $\sim 1.5 \cdot 10^5$ cm^{-3}	Wang and Nielsen (2003)
	Sporadic ionospheric layer in the range 65–110 km / electron density $\sim 8 \cdot 10^3$ cm^{-3}	Pätzold et al. (2005)
Titan	Ionospheric layer peak ∼1250 km / electron density $\sim 3.8 \cdot 10^3$ cm^{-3}	Wahlund et al. (2005)
	Atmospheric conductive layer at ∼60 km / electron density ∼650 cm^{-3}	Hamelin et al. (2007)
Jupiter	Ionospheric layer peak ∼1000 km / electron density $\sim 10^5$ cm^{-3}, another layer ∼2000 km with $\sim 10^4$ cm^{-3}	Schunk and Nagy (2000)
	Lower ionospheric layers (∼200 km) might attenuate HF radio waves	Zarka (1985a, 1985b)
Saturn	Ionospheric peaks from 1200–2500 km / electron density $\sim 5 \cdot 10^4$ cm^{-3}	Nagy et al. (2006)
	Low frequency cutoff of Saturn lightning suggests diurnal variation of factor ∼100	Kaiser et al. (1984)
Uranus	Two sharp ionospheric layers from 1500–2000 km with peak electron densities $\sim 10^5$ cm^{-3}	Lindal et al. (1987)
Neptune	Ionospheric layer peak ∼1400 km / electron density $\sim 2.5 \cdot 10^3$ cm^{-3}	Tyler et al. (1989)

used to simulate atmospheric lightning activity supposedly prevalent in the Archaean Earth. These two lines of research have since converged with many other aspects of planetary science. Thus, planetary atmospheric electricity has become a field that involves multiple disciplines such as atmospheric thermodynamics, heterogeneous chemistry, cloud physics, spectroscopy, electromagnetic wave propagation, remote sensing and natural hazards and spaceflight risk assessment.

The present contribution follows in the footsteps of earlier reviews on the subject which appeared in the scientific literature. Among these are Levin et al. (1983), Williams et al. (1983), Rinnert (1985), Russell et al. (1993), Desch et al. (2002) and Aplin (2006). It aims to give the reader an updated description of the latest advances and new understanding which relate to electrical phenomena in the solar system gained through observations, laboratory work, numerical simulations and theoretical studies. We limit this review to those processes occurring below the ionosphere, and thus shall not discuss auroral processes or radiation belt phenomena, unless they are strongly coupled to lightning activity.

1.1 Existing and New Observation Platforms and Technologies

1.1.1 Spacecraft

Cassini/Huygens: The Cassini/Huygens mission was launched more than 10 years ago in October 1997 and arrived at Saturn in July 2004. On its way to Saturn it made two flybys of Venus in 1998 and 1999, one of Earth in 1999, and one of Jupiter at the end of 2000. Instruments on the Cassini orbiter capable of detecting lightning are the ISS (Imaging Science Subsystem) and the RPWS (Radio and Plasma Wave Science) instrument. The ISS platform consists of two cameras (wide and narrow-angle), each of them equipped with a charge-coupled device (CCD) sensor of 1024 pixels squared (Porco et al. 2004). They have a large number of filters, spanning the wavelength range from 200 to 1100 nm, including a narrow-band H_α filter for the atomic hydrogen line at 656 nm. The RPWS instrument consists of three electric and magnetic antennas and various receivers in the frequency range from a few Hz up to 16 MHz (Gurnett et al. 2004). It is capable of detecting either lightning whistlers or HF radio emissions (also called "sferics") above the ionospheric cutoff frequency of the respective planet, and the three electric antennas enable polarization and direction finding measurements. The Huygens Probe landed on Titan in January 2005 and the PWA (Permittivity, Wave, and Altimetry) package of the HASI (Huygens Atmospheric Structure Instrument) was equipped with several sensors capable of detecting lightning (Fulchignoni et al. 2002). It was able to measure AC electric fields up to 11.5 kHz, and a special Schumann mode could measure the power spectral density below 100 Hz with 3 or 6 Hz resolution. Each AC electric field data packet consisted of 80 integrated spectra with either 32 (above 60 km) or 14 lines (below 60 km); each spectrum was also split, then integrated in 3 frequency ranges, to provide impulsive event dynamics over shorter time scales.

New Horizons: This Pluto-bound spacecraft was launched on January 19^{th} 2006 and made a Jupiter fly-by on February 28^{th}, 2007. It carries a 7-instrument payload, designed to study the surface properties of the icy worlds of the Pluto–Charon system and to monitor interplanetary dust and solar wind particles. The LORRI (Long Range Reconnaissance Imager) instrument consists of an 8.2-inch (20.8-centimeter) telescope with a CCD and provides images of high angular resolution, $\sim$5 µrad. This instrument detected multiple lightning flashes on Jupiter's night side (Baines et al. 2007; details in Sect. 3.1). The spacecraft also carries LEISA (Linear Etalon Infrared Spectral Imager) and ALICE—an ultraviolet imaging spectrometer which was capable of detecting the Ly-α nightglow on Jupiter (Gladstone et al. 2007).

Mars Express (MEX): This spacecraft was launched on June 2nd 2003, and entered a nearly-polar orbit around Mars on December 25th 2003. While the Beagle-2 Lander mission was lost, the MEX orbiter accomplished most of its intended scientific objectives. The main atmospheric instruments on board MEX are the Energetic Neutron Atoms Analyzer (ASPERA), the Radio Science Experiment (MaRS) for atmospheric and environmental sounding, the Planetary Fourier Spectrometer (PFS) for atmospheric composition and circulation, and the SPICAM, an ultraviolet and infrared atmospheric spectrometer. The MEX also carries a high-resolution stereo camera (HRSC) used for surface imaging. The spacecraft is equipped with the MARSIS instrument ionospheric and surface sounding radar, whose receivers could potentially detect electromagnetic impulses from Martian dust storm discharges.

Venus Express (VEX): Launched on November 9th 2005, this European spacecraft entered a Venusian orbit on April 11th 2006. It is an upgraded version of the MEX mission with similar instruments. The spacecraft monitors the atmosphere with an array of 7 instruments. VEX (but not MEX) has a magnetic field instrument called MAG, which is considered to be optimal for detection of lightning-associated electromagnetic bursts (Russell et al. 2006). The main camera on board is the Venus Monitoring Camera (VMC) that takes images of Venus in 4 narrow band filters from UV to near-IR all sharing one CCD. The spatial resolution is 0.2 km to 45 km per pixel, depending on the distance from the planet. The full disc of Venus is in the VMC field-of-view near the apocentre of the orbit. Additional instruments include the SPICAV (identical to the MEX SPICAM), the VeRa for radio sounding and the VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) which operates at wavelengths between 0.3 and 5 μm. The infrared capability of VIRTIS is especially well fitted to the thermal sounding of the night side atmosphere allowing a tomography of the atmosphere down to the surface.

Earth Orbiting Spacecraft: Monitoring of terrestrial lightning from space on a continuous basis was first achieved by the Optical Transient Detector (OTD), a payload on board the NASA Micro-Lab-1 satellite that was launched in April 1995. The orbital inclination of the satellite was 70 degrees and enabled the coverage of almost the entire planetary thunderstorm activity from an altitude of 740 km. The OTD instrument optically detects lightning flashes occurring within its $1300 \times 1300\ \text{km}^2$ field-of-view during both day and night. A statistical examination of OTD lightning data reveals that nearly $1.4 \cdot 10^9$ flashes occur annually on Earth, translating to a rate of 44 ± 5 flashes per second (Christian et al. 2003). The OTD was an engineering prototype for the LIS instrument on board the TRMM (Tropical Rainfall Measuring Mission) satellite which was launched in 1997 to a 35 degrees inclination orbit, that focused its lightning mapping capability on the tropics, reaching 90% detection efficiency of both cloud-to-ground and intracloud flashes. With additional instruments onboard such as the Precipitation Radar (PR), the Visible and Infrared Scanner (VIRS) and the TRMM Microwave Imager (TMI), this satellite provides unique insights into precipitation patterns in the tropics and the relationships between lightning and rain. The data from both instruments is readily available on-line at NASA's Global Hydrology and Climate Center (http://thunder.nsstc.nasa.gov/).

Terrestrial lighting is also being monitored by spaceborne VHF detectors on the FORTE and DEMETER satellites. The Fast On-orbit Recording of Transient Events (FORTE) satellite was launched on August 29th 1997, to a nearly circular, 70° inclination orbit. It carries two tunable receivers that have a 22 MHz analog bandwidth, covering the frequency range from 20 to 300 MHz (HF and VHF bands), as well as an optical sensor with a 10 nm passband filter centered at 777.4 nm. It also carries a single-element silicon photodiode (PDD), which has a 6% detection efficiency of cloud-to-ground flashes, and thus is able to geolocate only the strongest flashes (e.g., superbolts; Turman 1977). The DEMETER mission is reviewed by Parrot et al. (2008) in another chapter of this issue.

Boeck et al. (1994) utilized the space shuttle payload-bay cameras to observe the Earth's limb above thunderstorms and demonstrate that transient luminous events can be observed from low earth orbit. Such episodic observations were repeated with more sensitive instruments by Yair et al. (2004) and Blanc et al. (2004). The capability for a continuous monitoring of TLE activity on a global scale was achieved by the FORMOSAT satellite, launched on May 20th 2004 to a 99.1° inclination, 891 km high, circular orbit. The Imager of Sprites and Upper Atmosphere Lightning (ISUAL) payload comprises an array photometer, an intensified imager and a spectrophotometer with 6 wavelengths, covering the main emissions of sprites and elves. The global coverage of FORMOSAT enables detailed mapping of the occurrence of TLEs (see Sect. 2.1.2 below). The RHESSI satellite is being used to monitor terrestrial gamma flashes (TGFs), originally discovered by the BATSE instrument on board the Compton Gamma-Ray Observatory (see Sect. 2.1.3 below). There is now considerable evidence linking TGFs with lightning (Smith et al. 2005).

1.1.2 Telescopes

UTR-2: This is the world largest radio-telescope in the decametric frequency range (operated from about 8–32 MHz) located in Kharkov, Ukraine. It consists of 2040 dipoles and has an effective area of 150,000 m^2 (Konovalenko et al. 2001). Its sensitivity of a few Jansky (Jy) enables it to detect lightning from Saturn that is expected to produce a flux of the order of 100 Jy at Earth (Zarka et al. 2004).

LOFAR: The future Low Frequency Array (LOFAR) will be a large baseline next-generation radio-telescope that is being built in Northern Europe. It will operate in the frequency range from 30 to 240 MHz, and its effective area should be $>10^5$ m^2 (Kassim et al. 2004). Besides astronomical observations, it could also be used to monitor lightning on Saturn and Uranus (Zarka et al. 2004).

NASA/IRTF: This is the largest infrared telescope available for planetary science, with a 3-m diameter mirror. Several upgrades and technological improvements have been made and the observatory now contains five operational instruments: (a) SpeX, a 1–5 micron cross-dispersed medium-resolution spectrograph (b) CSHELL, a 1–5 μm high-resolution spectrograph; (c) MIRSI, a 5–25 μm camera and low-resolution spectrometer; (d) NSFCAM2, a 2048 × 2048 pixel, 1–5 μm camera with a 0.04 arcsec/pixel scale; and (e) Low-resolution 3–14 μm spectrograph and high-resolution spectrographs for 8–25 μm. The IRTF allocates 50% of its observation time to solar-system bodies and made numerous contributions to the study of the outer planets' atmospheres (Sánchez-Lavega et al. 2001; Orton et al. 2006; Simon-Miller et al. 2006; and many others). The IRTF is able to identify trace molecular constituents in planetary atmospheres, thus providing indirect evidence of the presence of lightning, based on the fact that lightning is a high-temperature discharge process that produces non-equilibrium chemical compounds (Bar-Nun 1975).

2 Lightning Activity and Atmospheric Electricity on Solid Surface Bodies

2.1 Earth

Hundreds of new papers and several comprehensive book chapters have been published since the brief phenomenology of terrestrial lightning activity given in Desch et al. (2002), the most comprehensive one is the book by Rakov and Uman (2003). We shall present here only those aspects that are essential for comparative studies of the meteorological and microphysical conditions conducive to the generation of lightning. Admittedly, there is a huge body of new knowledge concerning the properties of lightning initiation and propagation, the very nature of which may be different in alien circumstances. New techniques and observation systems have been developed that yield exciting insights into the intricate details of the lightning phenomenon. However, the limited scope of this review dictates a focus on the most basic and important aspects. Detailed information is found in the chapter by Stolzenburg and Marshall (2008) in this issue.

2.1.1 Lightning

Lightning on Earth is concentrated between ±60° latitude, with the large majority (>90%) above continental land-masses. The region of maximum lightning activity displays a distinct seasonal dependence and migrates with the Intertropical Convergence Zone (ITCZ) as it moves across the equator to the summer hemisphere. The global planetary rate was estimated by Christian et al. (2003) to be ∼45 flashes per second based on the OTD and LIS space-borne sensors, a frequency similar to that which was estimated based on Cassini's HF measurements during its Earth flyby in 1999 (70 s^{-1}, Gurnett et al. 2001). The global lightning activity is concentrated in the convectively active continental tropical regions, and shows a clear maximum around 16–17 LT and a minimum in the early morning hours 06–09 LT. The oceanic lightning activity has a marginal contribution to the global rate and is spread evenly along the day (the reader is invited to view the statistics published at http://thunder.msfc.nasa.gov/). Most lightning occurs inside thunderclouds (IC or intracloud flashes) and only the minority connects with the surface (CG or cloud-to-ground flashes). For obvious reasons, CG lightning discharges have been the main focus of research and the typical values of all their parameters are known quite accurately (see Table 1.1, page 7 in Rakov and Uman 2003). The details of the discharge process in its various stages are also well documented on the sub-millisecond scale (Table 1.2, ibid.).

In our solar system, cloud-to-ground lightning might be unique to Earth, because there are no similar conditions in any other planet to allow the propagation of a (stepped) leader from the clouds to the ground (with the possible exception of Mars). Thus, intracloud flashes are probably the typical type of planetary lightning and hence we devote more attention to their features. Intracloud discharges in terrestrial clouds often begin within the negative charge center and are accompanied by strong initial breakdown pulses which last 50–80 μs. They produce strong HF emissions whose amplitudes are 10 times larger than in CG flashes, and are termed "compact intracloud discharges". These discharges are thought to be responsible for the Trans-Ionospheric Pulse Pairs (TIPPs) detectable by satellites (FORTE; Jacobson and Light 2003) and ground-based VLF/LF sensors (Smith et al. 2004). TIPPs appear as pairs of very brief dispersed HF radio bursts, each lasting a few microseconds and separated by a few tens of microseconds (Massey and Holden 1995), that were identified as the direct and reflected signals of compact intracloud discharges.

Interestingly, Shao and Jacobson (2002) found the TIPPs observed with the FORTE satellite to be highly polarized emissions on the contrary to other VHF signals accompanying more common discharge processes like initial ground strokes, dart leaders or K-streamers. The intracloud discharge process is slow and the initial breakdown pulses are separated by 600–800 μs, a factor ∼10 longer compared to a CG flash. The processes in the late stages of intracloud flashes resemble the J- and K-changes found in the interstroke intervals of regular CGs. Recent advances in 3D VHF source mapping technology showed the bipolar nature of the intracloud discharge process (Thomas et al. 2001) and measured the peak powers in the 60–66 MHz pass-band where they varied from a typical minimum of about 1 W up to 10–30 kW. The radiation sources indicate the location of the main charge regions in a storm and the strongest ones where found to reside in the upper positive charge center. Coleman et al. (2003) also used 3D VHF mapping and showed good agreement between the altitudes of horizontal lightning channels and the altitudes of maximum electric potential (measured by balloons). Lightning flashes appear to deposit charge of opposite polarity in relatively localized volumes within the clouds, thus modifying the tri-polar state and creating a complex, multi-polarity structure (Stolzenburg et al. 2001; Stolzenburg and Marshall 2008, this isuue).

2.1.2 Transient Luminous Events

Transient Luminous Events (TLEs) is the collective name given to a wide variety of optical emissions which occur in the upper terrestrial atmosphere above active thunderstorms. Since their discovery these very brief, colorful phenomena have been studied from the ground, balloons, aircraft, the space shuttle, the ISS (International Space Station) and orbiting satellites. There is a growing body of literature which covers the phenomenology and theory of TLE generation (we refer the interested reader to the comprehensive volume edited by Füllekrug et al. (2006). Distinct classes and names were given to the various forms of TLEs, all of which allude to their rapid unpredictable nature: Jets, Sprites, Elves, Pixies to name but a few. Telescopic imaging (Gerken and Inan 2001) and the use of high-speed imagers (Cummer et al. 2006a) have greatly improved the knowledge of the fine structure of these emissions and their initiation and propagation mechanisms. The inhomogeneous and transient variability of the terrestrial atmosphere at these heights is believed to play a crucial role in the initiation of TLEs—e.g. gravity waves, chemical reactions and meteors modify the local electrical properties of the mesosphere, making it more conducive to electrical breakdown processes. The molecular basis for the emissions observed in sprites is thoroughly discussed by Pasko (2007). Sprites are usually associated with intense positive cloud-to-ground lightning and are initiated at a height of 70–80 km, from which they propagate in visible tendrils downwards and upwards. Elves occur higher up, around 90–95 km above the ground and are a result of the interaction between the propagating Electromagnetic Pulse (EMP) from the lightning and the ionosphere (Inan et al. 1997). They have not been found to correlate with the polarity of the parent lightning.

A new class of TLE which extends from cloud tops all the way up toward the ionosphere was discovered by Pasko et al. (2002) and Su et al. (2003) and was nicknamed "gigantic jets" (Fig. 1). It is believed to short-circuit the cloud charge to the upper atmosphere. The Earth's global rate of TLEs was estimated to be a few per minute based on observations from the space shuttle (Yair et al. 2004), the International Space Station (Blanc et al. 2004) and from the continuing monitoring by the FORMOSAT satellite (Cummer et al. 2006b). Though TLEs have not been detected in any other planetary atmosphere, their existence is theoretically possible and they are likely to occur (Yair et al. 2007).

2.1.3 Terrestrial Gamma Ray Flashes (TGFs)

Relativistic runaway electrons were considered by various authors (e.g. Gurevich et al. 1992; Roussel-Dupré and Gurevich 1996; Lehtinen et al. 1997) as a potential source of ionization and optical emissions related to sprites. In fact, runaway electrons necessarily must produce X-rays and gamma rays in interaction with air particles. However, due to their attenuation in

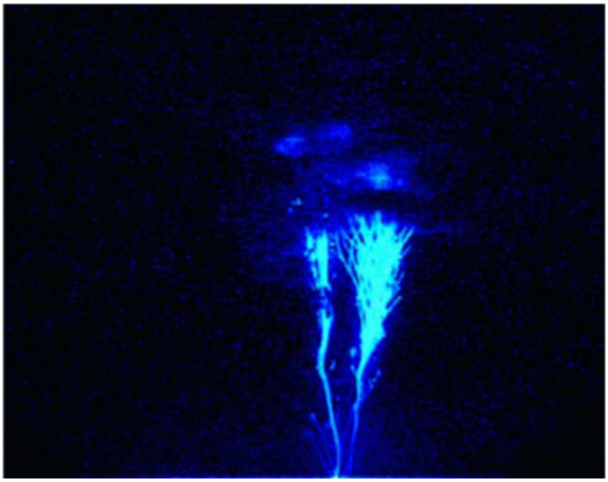

Fig. 1 Enhanced color image of a gigantic jet, observed by Pasko et al. (2002). The propagation of the discharge was from cloud top until the base of the ionosphere at ~95 km

air, their detection is difficult. Suszcynsky et al. (1996) showed that for energies of the order of MeV, the X-ray attenuation length is around 100 m to 1 km at thunderstorm altitudes. Suszcynsky et al. (1996) also reviewed the ground-based and low-altitude measurements of previous X-ray measurements and remained somewhat skeptical about positive results. But, X-ray observations with balloon-borne measurements within thunderclouds were reported by Eack et al. (1996), and Moore et al. (2001) associated their X-ray measurements with stepped leaders from ground flashes observed on a mountain top. The first observations of Terrestrial Gamma Ray Flashes (TGFs) from space were related to thunderstorms on Earth by Fishman et al. (1994): The Burst and Transient Signal Experiment (BATSE) onboard the Compton Gamma Ray Observatory detected 50 X-ray bursts with a typical duration of a few milliseconds in four years. This detection was later confirmed by the RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) satellite, which typically detects 10 to 20 TGFs per month (Smith et al. 2005). Dwyer and Smith (2005) inferred from Monte Carlo simulations of TGF spectra in comparison with RHESSI observations that the TGFs might stem from a source altitude around 15–21 km, which was also confirmed by Williams et al. (2006). Dwyer et al. (2005) also reported the production of X-ray bursts by laboratory sparks in air. In a recent paper, Stanley et al. (2006) link TGFs to intracloud discharges which transport electrons upward. Although the detection of atmospheric gamma-ray bursts and X-rays are somewhat difficult due to their attenuation in the surrounding medium, they might open a new wavelength window for future detection and studying of lightning also in other planetary atmospheres.

2.2 Venus

Venus is completely covered by a thick, optically opaque layer of sulfuric acid clouds, which rotate faster than the planet (super-rotate). There are at least three cloud decks, between ~50 and 70 km above ground, whose altitude, composition and size distribution (in 4 discrete particle-size modes) was derived from descent probes measurements. There is little evidence for small scale convective structures or for vigorous vertical motions within this essentially stratus-like planetary scale envelope. Venus has an induced "magnetosphere", where the interplanetary magnetic field is draped around the planet. After the Magellan radar mapping mission of the early 90s, Venus has become in the words of Schilling (2005) "*our neglected* *neighbor*", and relatively little research effort was directed to what was once considered to be "*our sister planet*". As a result, the controversy concerning the very existence, location and frequency of lightning on Venus remains unresolved.

Radio wave observations that were interpreted as likely due to lightning (Ksanfomaliti 1979; Russell 1991; Russell et al. 1993, 2006) have not been firmly confirmed by measurements in the visible spectrum, though two optical observations are claimed—one performed onboard Venera 9 (Krasnopolsky 1980) and another with a ground-based telescope (Hansell et al. 1995). Similar radio waves detected by the Galileo and Cassini spacecraft during their respective flybys were given different interpretations (Gurnett et al. 1991, 2001). The crux of the matter is that apart from that single attempt by Hansell et al. (1995), no systematic search for Venusian lightning by a dedicated instrument on a spacecraft or on the ground was conducted, and the existing optical and electromagnetic data is insufficient to elucidate the matter completely. As Desch et al. (2002) state: "*Progress in resolving the central controversy of Venusian lightning will probably require either an extensive ground-based optical search or an orbiter with a camera and HF receiver*". The non-detection of HF signals by the Cassini spacecraft (Gurnett et al. 2001) sets a lower limit on lightning activity, but it can be argued that the short sampling time during the two flybys coincided with a quiet period with subdued lightning activity, and thus misrepresents the true planetary rate (see Zarka et al. 2008 in this issue for further discussion). The little numerical work done on the possible charging mechanisms and electrical field build-up within Venusian clouds all date back to the early 80 s, and lack the sophistication of contemporary terrestrial cloud models (reviewed by Yair 2008 in this issue). This leaves the question on the ability of the multiple stratiform cloud layers in Venus to actually separate sufficient charge for electrical breakdown largely open.

Recently, high-resolution spectra of Venus in the NO band at 5.3 μm were acquired using the TEXES spectrograph at the IRTF (Krasnopolsky 2006). An NO mixing ratio of 5.5±1.5 ppb was detected below 60 km. The photochemical impact of the measured NO abundance is significant and cannot be explained by chemical reactions induced by cosmic ray ionization alone, leaving lightning as the only possible source (Krasnopolsky 2006). The required flux of NO corresponds to a lightning energy deposition of 0.19 ± 0.06 erg cm^{-2} s^{-1}. For an assumed flash energy of $\sim 10^9$ J, the global flash rate should be ~ 90 s^{-1} or ~ 6 km^{-2} y^{-1}. Such a high flash rate is consistent with the analysis of the Pioneer Venus Orbiter (PVO) VLF data, that yielded a rate of 250 s^{-1} based on the assumption that lightning occurs only between $\pm 30°$ latitude and during 18–24 h LT (Ho et al. 1995). Even if that calculation can be considered overly optimistic, additional supporting evidence for at least some lightning activity in the Venusian atmosphere was given by Strangeway (1995), who maintained that lighting is the most probable explanation for the plasma waves detected at low altitudes in the nightside ionosphere of Venus by the PVO. The Venus Express mission has yet to produce optical images of lightning by the VMC and VIRTIS instruments. However, Russell et al. (2007) reported clear indications of lighting activity. A 128 Hz sampling rate was used by MAG for 2 minutes at periapsis for each orbit until December 2006, and from that time onwards the high-rate sampling switched to 10 minutes at periapsis. The received data show elliptically polarized signals that propagate along the background magnetic field. When the field is horizontal the waves are not observed, yet at larger inclinations the wave energy can reach the instrument in the whistler mode. Most recently, Russell et al. (2007) discussed the measurements obtained in 37 orbits of VEX that took place between May and June 2006. When VEX passed through the magnetic field lines at altitudes around 300 km (which is above the Venusian ionopause and in a magnetic field strength ~ 23 nT), the MAG instrument observed magnetic field fluctuations of the order of 0.1 nT indicative of whistler mode waves. The fluxgate magnetometer

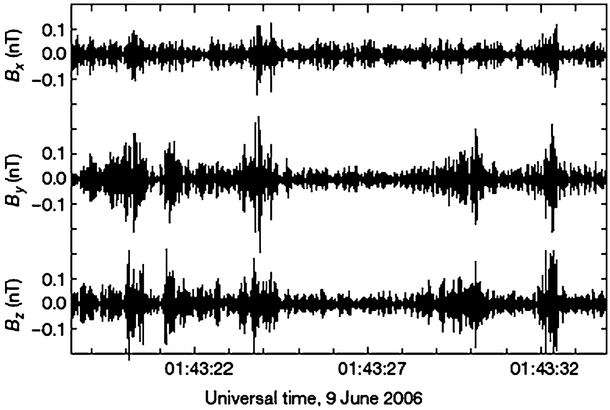

Fig. 2 The three components of the magnetic field as recorded by the fluxgate magnetometer (MAG) on-board the Venus Express spacecraft. Signals exhibit repeated bursts with alerting amplitudes and duration, hinting at lightning as the probable source. The x-component is towards the Sun, z along the orbit plane and y in opposite planetary motion. This measurement was made from a range of 305 km of the Venusian surface as the spacecraft was travelling at 24,000 km/h (from Russell et al. 2007)

detected bursts of clear signals, with rapidly varying amplitudes and variable durations and intermissions between successive bursts (Fig. 2). The typical durations were found to be 0.2–0.5 s.

The possibility that these signals were due to spacecraft interference was excluded by subtracting the signals received by the two magnetometers. Russell et al. (2007) argues that there is no other possible source for natural whistler-mode waves propagating from the atmosphere to the ionosphere except lightning. However, the possibility that these waves stem from ionospheric plasma waves should not be discarded yet, since on Earth lightning whistlers at comparable altitudes are typically a factor of 10 shorter in duration (e.g. Holzworth et al. 1999) than the VEX-MAG whistler mode waves. Their deduced planetary flash rate on Venus, based on the detector footprint of 0.06% of the planet's surface, is 50 s^{-1}. Such a flash rate is comparable to Earth's and is inconsistent with the lack of correlative optical data. As the mission progresses there is hope that optical signatures will be received on top of the robust electromagnetic data.

Obviously, lightning on Venus should be completely intracloud, namely occurring within a given cloud layer or between layers. This is because the height of the cloud layer above the surface and the extreme atmospheric pressure requires an extremely high electric filed for cloud-to-ground breakdown to be produced. It is possible that Venusian intracloud discharges will not resemble terrestrial intracloud flashes, and will have different signatures in the electromagnetic and optical bands. It may well be that the luminosity of Venusian lightning is significantly lower than that of terrestrial ones and that they are completely obscured by the upper cloud layers. Hopefully future missions such as the Japanese Planet-C (Takahashi 2008, this issue) will enable us to conduct better and prolonged observations.

2.3 Mars

The Martian environment has been studied using remote sensing and in situ observations, but the electrical properties, such as those related to atmospheric electricity, are still poorly known. The atmosphere consists mostly of CO_2 with a mole fraction of $\sim$0.95; the near-surface atmospheric density is about 70 times smaller than on Earth and the electron conductivity is a few orders of magnitude higher than on Earth at similar altitudes. Surface conductivity estimates evaluated by theoretical models vary between 10^{-12} and 10^{-7} Sm^{-1}. Berthelier et al. (2000) tentatively restrict the range down to 10^{-12}–10^{-10} Sm^{-1}. Furthermore, the composition of the surface at low and high latitudes is quite different due to the presence of ice deposits in the polar region, suggesting large variations in surface conductivity with latitude. Electrical discharges on Mars certainly would differ from that on Earth because the environmental properties and discharge processes are markedly different on the two planets (Farrell and Desch 2001). Aplin (2006) presents a comprehensive review of atmospheric electricity that also includes relevant information about the Martian environment.

Large electric fields have been measured in terrestrial dust storms, dust devils and regular wind-blown saltation (Stow 1969; Farrell et al. 1999; Renno et al. 2004; Schmidt et al. 1998). Melnik and Parrot (1998) used a numerical model to study the electrification of Martian dust storms and predicted that large electric fields are generated in them. In dust storms, charge transfer occurs during collisions between sand/dust particles with each other and the surface. After collisions, the smaller dust particles become negatively charged with respect to the larger sand particles and the surface, although the exact mechanism by which this occurs is still under debate (Lowell and Truscott 1986; Desch and Cuzzi 2000; Kok and Renno 2008). Gravitational and aerodynamic forces then separate the heavier, positively charged particles from the lighter, negatively charged particles. The resulting charge separation produces the observed bulk electric fields. On Earth these fields can exceed 100 kV/m, but on Mars they are limited by the electric breakdown of the thin Martian air at about 20 kV/m, except perhaps at very short distances (smaller than a few cm) from the surface. This happens because the breakdown electric field decreases with the distance between electrodes and the value of 20 kV/m is for a distance of the order $\sim$1 m (Naidu and Kamaraju 1999; Ito and Terashima 2002).

The maximum charge of airborne dust particles can be calculated assuming that during saltation, charging is limited by field emission (Bernhard et al. 1992) in collisions between dust and sand particles. Then, a micro-discharge occurs while the particles move away from each other and the particles are left with a residual charge of the order of that necessary to produce electric discharges (Renno et al. 2003). Negatively charged dust particles of a few μm in diameter then rise with the updraft while the larger positively charged sand particles stay in the saltation layer. This produces charge separation and the bulk electric fields observed in dusty phenomena. Then, knowing the dust particle concentration and distribution, the bulk electric field can be calculated. Renno et al. (2004) showed theoretical evidence that Martian dusty phenomena should emit non-thermal microwave radiation, and supported it by the observation of terrestrial dust devil analogues. More recently, Renno and his collaborators found evidence that electric discharges in Martian dust storms not only should emit non-thermal radiation but also might excite Schumann resonance in the surface–ionosphere cavity.

Delory et al. (2006) and Atreya et al. (2006) showed that the electric activity on Mars may potentially produce large quantities of hydrogen peroxide, a powerful oxidant that could make the surface inhospitable to life as we know it. Similar to the observations of Venus, the TEXES spectrograph on the IRTF was used to study the Martian atmosphere. Measurements on one NO line show some power increasing over the continuum, hence suggesting that discharging processes might play a role in the atmosphere (Krasnopolsky 2006). The inferred NO concentration is above the predictions of photochemical models by a factor of 3 but no definite explanation is provided for such a difference.

2.4 Titan

Saturn's largest satellite Titan (radius of 2575 km) possesses a thick atmosphere dominated by nitrogen and methane with a surface pressure and temperature of 1.5 bar and 94 K, respectively. Since the Voyager 1 flyby of Titan in November 1980 the possibility of lightning

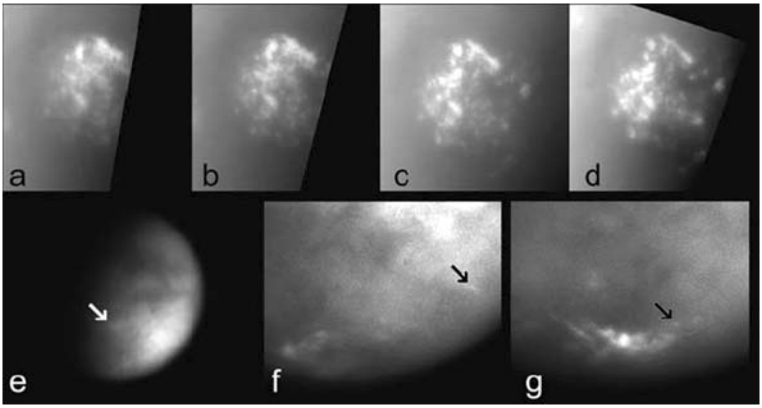

Fig. 3 Tropospheric cloud features observed by Cassini/ISS on Titan. The sequence **a**–**d** shows the development of Titan's South polar cloud as imaged on July 2, 2004. Panels **e**–**g** show three examples of discrete mid-latitude clouds, which are marked by *arrows*. They were imaged on May 29, October 23 and 25 (all 2004), respectively (taken from Porco et al. 2005a). Could lightning discharges develop in such clouds?—Cassini/RPWS did not detect lightning associated radio emissions

on Titan has been investigated by theoretical and experimental studies of its complex atmospheric chemistry (Gupta et al. 1981; Borucki et al. 1984, 1988; Navarro-González et al. 2001), mostly with positive and promising results. The non-detection of Titan lightning radio emissions by Voyager's radio instrument (Desch and Kaiser 1990) still could be explained by Titan's low or episodic flash rate (Lammer et al. 2001), and Tokano et al. (2001) developed a model for thundercloud and lightning generation on Titan.

The multiple Cassini flybys of Titan as well as the descent of the Huygens Probe on its surface in January 2005 revealed a fascinating Earth-like landscape with lakes and river beds, bright high-land regions and dark flat lowlands. Besides geological processes, this landscape is shaped mostly by weather, because there is wind, haze, drizzle, and most likely rain in Titan's atmosphere (Tomasko et al. 2005; Tokano et al. 2006). The Earth-based infrared observations of methane clouds on Titan (Griffith et al. 1998) were clearly confirmed by Cassini imaging observations (Porco et al. 2005a; see Fig. 3). Convective clouds over the South pole of Titan were observed for several months in 2004 before they vanished in December of that year and reappeared shortly in December 2005 (Rodriguez et al. 2007). Furthermore, elongated mid-latitude tropospheric clouds (Porco et al. 2005a) as well as ethane clouds (Griffith et al. 2006) have been observed. The most likely places for lightning on Titan are the convective-type methane clouds as those that appeared over the South Pole. Such clouds were modeled by Hueso and Sánchez-Lavega (2006) who found strong updrafts with velocities up to 20 $\mathrm{m\,s^{-1}}$ in such methane storms. In a similar model Barth and Rafkin (2007) got mixing ratios of cloud particles of the order of 1–10 $\mathrm{g\,kg^{-1}}$. Such updraft velocities and mixing ratios are comparable to terrestrial thunderstorms (Rakov and Uman 2003).

Despite such promising conditions, the existence of lightning on Titan has not been proven yet. Fulchignoni et al. (2005) reported the possible detection of the signature of lightning by the Huygens Atmospheric Structure Instrument (HASI), that measured impulsive electric field events with the mutual impedance receiver during the descent of the Huygens Probe. These impulses, recorded in the frequency range from 180 Hz to 11.5 kHz, could be due to lightning, but one has to be careful in the interpretation with impulsive signals since they could be as well caused by interferences from on-board instruments or particle impacts.

Nevertheless, the number of events detected during the descent of the Huygens Probe establishes a maximum stroke rate not higher than 1% compared to stratospheric balloon campaigns. A peak in the power spectrum detected at 36 Hz is most likely not a lightning caused Schumann resonance since its frequency is not consistent with most models of Titan's ionospheric cavity (Simões et al. 2007), and its signal level is also much too high. Béghin et al. (2007) favor waves created in Titan's ionosphere as a possible source, and future laboratory experiments at low temperatures could show if the 36 Hz line is simply created by a mechanical vibration of the HASI antennas or not. The acoustic sensor on-board Huygens did not record any thunder claps (Grard et al. 2006). The Huygens Probe also detected an ionized layer at about 60 km altitude with a maximum conductivity of 3 nS/m (Hamelin et al. 2007), which is a few times higher than the surface conductivity measured at the landing site (Grard et al. 2006). This layer, induced by cosmic rays, certainly plays a role in atmospheric electrification, aerosol kinetics, and on the possible global electric circuit of Titan.

The Cassini/RPWS instrument searched for radio emissions from Titan lightning, but nothing was found during any of the first 35 Titan close flybys (Fischer et al. 2007a). In case of a Titan lightning storm RPWS should easily detect bursty signals above Titan's ionospheric cutoff frequency of about 500 kHz (Bird et al. 1997) that also show a quadratic fall-off of signal intensity with spacecraft distance. The non-detection of RPWS tells us that Titan lightning is an extremely rare event if it exists at all. Despite the similarities between methane clouds on Titan and terrestrial thunderclouds, one key question is still whether an efficient microscale electrification process can work in a Titan cloud given the low relative dielectric constant of 1.7 of methane. The RPWS result does not rule out the existence of other forms of atmospheric electricity like corona discharges. The search for Titan lightning with RPWS will continue at least until the end of Cassini's extended mission in mid-2010, which will increase the total number of close Titan flybys to 70.

3 Lightning Activity and Atmospheric Electricity at the Gas Giants

Lightning is a very interesting phenomenon in the atmospheres of the four gas giants, Jupiter, Saturn, Uranus and Neptune. It is likely to be more powerful than terrestrial lightning and also acts as a diagnostic tool of the dynamics of the respective atmosphere. Equilibrium cloud condensation models (Atreya and Wong 2004) suggest a similar cloud structure for Jupiter and Saturn, as well as for Uranus and Neptune. For Jupiter and Saturn the outermost cloud layer consists of ammonia (NH_3) ice particles, which is followed by an intermediate ammonium hydrosulfide cloud layer (NH_4SH) and a deep water cloud (H_2O). For Uranus and Neptune there should be a methane (CH_4) ice particle cloud around the 1-bar level followed by nearly the same cloud layering as on Jupiter and Saturn, except that also hydrogen sulfide (H_2S) should be present at the same altitude where ammonia condenses (de Pater et al. 1991).

At Jupiter, the water cloud at a pressure level around 4–5 bar has been identified as the source of lightning by optical observations. Usually, the bright dots due to Jovian lightning imaged by the cameras extend over more than one hundred kilometers, since the flashes are scattered at various cloud layers. A Monte-Carlo model of this scattering process has lead Borucki and Williams (1986) as well as Dyudina et al. (2002) to the same (already mentioned) conclusion regarding the origin of Jovian lightning. The non-detection of optical emissions from lightning on Saturn (Burns et al. 1983; Dyudina et al. 2007), Uranus (Smith et al. 1986), and Neptune (Borucki and Pham 1992) could be due to very deep atmospheric sources, as well as scattered ring light. The deep water cloud is a primary candidate, because it is located around the freezing level for all four gas giants and cloud particle charging could work in a similar manner as in terrestrial thunderclouds. The smaller gravitation at Saturn, Uranus, and Neptune compared to Jupiter leads to smaller temperature lapse rates and the water clouds condense at higher pressure levels. According to the models of Atreya and Wong (2004) the base of the water ice cloud should be around 5 bars and 10 bars for Jupiter and Saturn, respectively, and around 40 bars for Uranus and Neptune.

A decisive parameter for the possibility of lightning discharges in planetary atmospheres is the value of the breakdown electric field for the specific atmosphere. The measured value for dry terrestrial air under standard conditions is $3 \cdot 10^6$ V/m and it scales with pressure. Such high electric fields have never been directly measured in thunderclouds and observed values are typically smaller by one order of magnitude (Rakov and Uman 2003) suggesting that besides the conventional breakdown the so-called runaway breakdown might play an important role in initiating lightning discharges. For Jupiter's atmosphere, Yair et al. (1995a) estimated the conventional breakdown field to be $2.3 \cdot 10^6$ V/m at a pressure of 5 bars. Recent modeling work by Dwyer et al. (2006) indicate that the electric field threshold for the so-called runaway breakdown could be 10 times smaller in the atmospheres of the gas planets compared to the conventional breakdown field. Kinetic calculations of runaway and conventional breakdown fields in planetary atmospheres have been performed by Sentman (2004) and are supplemented in the paper by Roussel-Dupré et al. (2008) in this issue. The hydrogen–helium atmospheres of the gas planets facilitate electric breakdown, but breakdown fields are still larger than at Earth at the pressure level where the deep water clouds reside.

3.1 Jupiter

Lightning at Jupiter was first detected optically with the camera on-board Voyager 1 (Cook et al. 1979), and further observations were made with Voyager 2 as well as by Galileo (Little et al. 1999). The Voyager plasma wave instrument detected lightning whistlers in Jupiter's magnetosphere (Gurnett et al. 1979), and sferics attributed to lightning were observed with the Galileo Probe inside Jupiter's atmosphere (Rinnert et al. 1998). These observations as well as the theoretical modeling of water clouds in Jupiters's atmosphere (Gibbard et al. 1995; Yair et al. 1995a, 1995b) have been extensively reviewed by Desch et al. (2002). Here we will focus on the recent optical observations obtained during the Jupiter flybys of Cassini at the end of 2000 and New Horizons in 2007, respectively.

Nightside images by the Cassini/ISS camera using the H_α filter revealed four lightning clusters, one at 24°N (North), one at 34°N, and two were repeated observations of the same storm located around 14°S (South; all planetocentric latitudes), in the turbulent wake region of the Great Red Spot (Dyudina et al. 2004). The observations were performed from a relatively large distance (140 to 200 Jovian radii). To diminish the scattered light, ISS used the narrowband H_α filter. Interestingly, the H_α line was about ten times weaker than expected from previous Galileo observations and laboratory simulations of Borucki et al. (1996) of the Jovian lightning spectrum. This could suggest that lightning is generated in atmospheric layers even deeper than 5 bar or that simply lightning frequency and intensity or cloud coverage varied between Galileo and Cassini observations (Dyudina et al. 2004). Cassini/ISS also studied the dayside appearance of the Jovian lightning storms.

On its way to Pluto and the Kuiper Belt, the New Horizons spacecraft flew by Jupiter as close as 32 Jovian radii at the end of February 2007. Recent observations by the spacecraft as well as ground-based thermal imagery have in fact revealed that the Jovian cloud cover in 2007 has thinned substantially since the Cassini 2000 flyby (Baines et al. 2007). Furthermore, the New Horizons LORRI (Long Range Reconnaissance Imager) camera identified

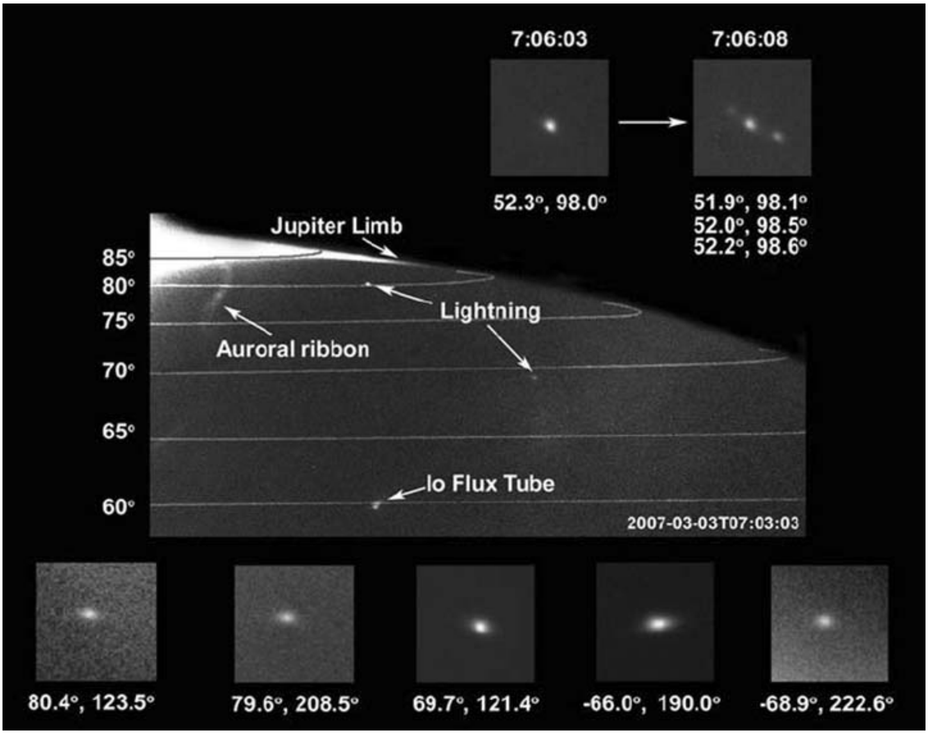

Fig. 4 Jovian lightning flashes as imaged by New Horizons/LORRI at various latitudes (planetographic) and longitudes. Exposure time was typically 5 seconds, and the spatial extension is due to diffusive scattering of flashes originating near the 5-bar water cloud level by aerosols and clouds above (taken from Baines et al. 2007)

Jovian lightning at high latitudes up to 80°N and 74°S (planetographic). Figure 4 displays some representative lightning flashes. Previous lightning observations have found Jupiter lightning only at lower latitudes, typically at the southern edges of westward-moving jets in regions of cyclonic shear (Borucki and Magalhaes 1992). New Horizons has found flashes also at the anticyclonic sides of eastward jets (60°S and 66°S), and the polar strikes (80°N, 74°S) are located in regions of relatively weak winds. All investigating spacecraft (including New Horizons) have found Jovian lightning to be most optically active around 50°N (Baines et al. 2007). Jupiter lightning is more powerful than terrestrial lightning, since the optical energy of a Jovian flash is of the order of 10^9 J, which corresponds to the typical *total* energy of a terrestrial flash (the median value for the optical energy in terrestrial lightning is $4.5 \cdot 10^5$ J; Kirkland et al. 2001). When considering the optical efficiency of the Jovian atmosphere (Borucki and McKay 1987), the total energy of a Jovian flash is $\sim 10^{12}$ J, comparable to terrestrial “superbolts” (Turman 1977). These estimates were corroborated in the numerical simulations by Yair et al. (1995b).

3.2 Saturn

Following the Voyager discovery (Warwick et al. 1981) and extensive studies (see e.g. the review by Zarka 1985a, 1985b), our knowledge about atmospheric electricity at Saturn has been greatly increased by the Cassini mission and this is reviewed in more detail in a separate article in this issue by Fischer et al. (2008). Several thousands of lightning sferics termed SEDs (Saturn Electrostatic Discharges) have been measured by Cassini/RPWS in six SED storms (Gurnett et al. 2005; Fischer et al. 2006, 2007b), but only one lightning whistler has been identified (Akalin et al. 2006). As opposed to Jupiter, until now only two latitudes at Saturn (whistler latitude excluded) have been found to produce lightning storms and these are the equatorial region and the "storm alley" at 35°S. The lightning flashes on Saturn have not yet been detected optically, most probably because the lightning source is located very deep in Saturn's atmosphere, approximately at the 10-bar level. But, Cassini/ISS imaged prominent cloud features in Saturn's atmosphere, whose occurrence, longitudinal drift rate, and brightness were strongly related to the SEDs (Porco et al. 2005b; Dyudina et al. 2007). Images of these cloud features can be found in this issue in the article by Fischer et al. (2008). During the Cassini mission there have been long time intervals with no SED activity. A giant lightning storm in early 2006 (Fischer et al. 2007b) was followed by 21 months of "silence", but a seventh SED storm started in the end of November 2007. The intense radio signals of SEDs (about 10^4 times more powerful compared to HF radio emissions from terrestrial lightning) have been detected also by the giant UTR-2 radio-telescope in the Ukraine (Konovalenko et al. 2006). SED characteristics and implications for ionospheric studies are discussed in Zarka et al. (2008) in this issue.

3.3 Uranus and Neptune

High frequency radio signals similar to SEDs have been detected by the Voyager 2 radio instrument at Uranus and they were termed UED for Uranus Electrostatic Discharges (Zarka and Pedersen 1986). At Neptune Voyager 2 detected 16 lightning whistler like events (Gurnett et al. 1990) as well as 4 possible lightning sferics (Kaiser et al. 1991). Since no other spacecraft except Voyager 2 has ever visited Uranus and Neptune, the progress in our knowledge concerning lightning activity on those two icy giants has been limited in the last years. Considerable progress has been made concerning Earth-based cloud observations of Uranus and Neptune in the infrared as well as visible wavelength region (e.g. Karkoschka 1998; Hammel et al. 2001; Roe et al. 2001; de Pater et al. 2002; Gibbard et al. 2003; Sromovsky and Fry 2005; Irwin et al. 2007). However, the lightning source might be in the water clouds located at a pressure level of about 40 bar, which is not accessible with these observations (Encrenaz et al. 2004). On the other hand, using a particle-growth and charge-separation model Gibbard et al. (1999) suggested that lightning is inhibited in the deep water or NH_4SH cloud because of the high atmospheric pressures there and that lightning seems possible in the H_2S–NH_3 cloud layer. Finally, Zarka et al. (2004, 2008) concluded that the sensitivity of the future giant Low Frequency Array (LOFAR) would allow us to detect and monitor lightning activity on Uranus (but not on Neptune) from Earth.

4 Laboratory Experiments

The early work done in laboratories in order to predict and to determine the production of chemical compounds by lightning in planetary atmospheres is discussed in detail by Desch et al. (2002), and we shall briefly touch upon some results that are of special relevance to on-going missions. Conceptually, these experiments are mostly based on discharging electrical sparks or on producing high-temperature plasma (LIP or laser induced plasma) inside a vessel containing the proper gas mixture at the relevant temperature and pressure, simulating the atmosphere being studied. Alternatively, concentrated lasers can be used to produce shock waves in order to study shock-induced chemistry. Borucki et al. (1996) have obtained the spectra of simulated lightning in gas mixtures of the atmospheres of Jupiter, Venus and Titan, by observing laser-induced plasmas with a scanning spectrometer and an optical multi-channel analyzer in the range 380–820 nm. The results show that atomic line and continuum dominate the spectra, with some weak molecular band from CN for Venus and Titan. At higher pressures, the dominance of the continuum over the atomic spectra increased and some lines disappeared. That work was a continuation of earlier experiments reported by Borucki and McKay (1987) which were aimed at obtaining the optical efficiencies of different atmospheres, namely, the capability of lightning light emanating from the deep atmosphere to be detected by a sensor on an orbiting spacecraft. The results showed that the fraction of the energy in lightning discharge channels that is radiated in the visible spectrum is similar for Earth, Venus and Titan, but quite different for Jupiter. However, this conclusion can be challenged based on our lack of detection, after numerous orbits, of visible light from flashes neither on Venus (Sect. 2.2) nor on Titan (Sect. 2.4). Arguably the assumption that electrical discharges are essentially similar to terrestrial flashes may be incorrect and it may well be that the characteristics of flashes in these two atmospheres is completely different (for example, slower rise-time, shorter channels, smaller peak currents and lower total energies). This calls for re-evaluation of the simulation philosophy of planetary lightning in laboratory-type atmospheres.

Due to its unique (pre-) biological aspect, considerable attention is being dedicated to the study of Titan's atmosphere. The notion that lightning can produce disequilibrium chemistry and lead to the formation of amino-acids and other complex organic compounds in its N_2-based atmosphere is not new and is considered, in the words of Desch et al. (2002), "*a tantalizing possibility*". Numerous new publications appeared since that review, especially in the exobiology literature, with a focus on production of organic pre-biotic chemical compounds by electrical processes. Navarro-González et al. (2001) studied the chemical effects of corona and lightning discharges in CH_4–N_2 mixtures. They found that lightning is approximately 2 orders of magnitude more efficient than corona discharges in producing hydrocarbons and nitriles, and that corona discharges are producing linear and branched hydrocarbons whereas lightning produces mainly unsaturated ones. Majumdar et al. (2005) studied reactions in CH_4/Ar and CH_4/N_2 gas mixtures at ambient pressures of 250–300 mbar. The products were higher order hydrocarbon molecules, typically C_nH_m with n up to 9, and also different functional CN groups. In a different type of experiment, Somogyi et al. (2005) studied the chemical reactions taking place in Titan's stratosphere, by exposing a mixture of 5% CH_4 and 95% N_2 to an AC electrical discharge at a temperature of 195 K inside a glass reaction vessel. The chemical reactions produced a thin layer of tholin on the wall, that was scraped and analyzed by mass spectrometry using electrospray ionization (ESI) and laser desorption (LD) techniques. The samples mimic the chemistry of aerosol particles in Titan's upper atmosphere, exhibiting the general formula of $C_xH_yN_z$. Most recently, Plankensteiner et al. (2007) conducted discharge experiments in order to simulate the chemical evolution on the surface of Titan by allowing the hydrocarbon chemistry to be exposed to water ice.

Electric discharges of 60 kV and 60 mA were pulsed with 5 Hz into the reaction chamber, which was kept at a pressure of 1.46 bar (Titan's atmospheric surface pressure) and at a temperature of $-32°C$. One electrode of the discharge gap was situated below a layer of water ice simulating discharges into Titan's surface. The results showed a robust production of C–H–O, C–H–N and C–H–O–N compounds including several molecules important for the formation of amino acids and nucleic acids. The uniqueness of this new experiment is the introduction of oxygen atoms into the compounds, believed to be a "first step" in any possible chemical evolution on the surface of Titan.

Interesting experiments were conducted in rarefied gas mixtures subjected to high external voltage in order to study the light emissions from transient luminous events (namely sprites). This type of discharge is very different to the high-energy high-temperature regime of LIP experiments. The first successful set of experiments was conducted by Williams (2001) for an N_2–O_2 mixture. The optical spectrum in the (red) positive column was found to resemble the spectrum of the sprite body as observed by Hampton et al. (1996). Lately, Goto et al. (2007) conducted similar experiments and proceeded to simulate a Venus-like composition of nearly pure CO_2 in different pressures. The results of the Venus experiment show dominance of the oxygen atomic line O 777.6 nm (the one used for lightning detection by Hansell et al. 1995), with additional CO and CO_2 lines at shorter wavelengths. This type of experiments is useful for searching for sprites above the clouds of other planets (see Takahashi 2008, in this issue).

5 Summary and Future Prospects

Considerable progress has been made in our understanding of lightning discharges since the latest review by Desch et al. (2002), and new insights have been gained from observations of electrical activity on other planets. Additionally, laboratory studies have shed light on the physics of charging and discharging processes in the atmospheres of other planets. The continuation of observations from spacecraft and ground-based instruments is bound to increase our inventory of data, and to enable us to gain deeper understanding of one of the basic phenomena in nature. At Venus the VEX mission will continue to increase our knowledge of atmospheric electricity at "our sister planet". The occurrence of the detected whistler-mode waves (Russell et al. 2007) as a function of local time should be evaluated. The future Japanese Planet-C mission (to be launched in 2010) will have a sensitive camera on-board for the detection of optical emissions from lightning and sprites. On our own planet Earth, atmospheric electricity is under investigation by an increasing number of scientists. The future Earth satellite mission, Taranis, described in this issue by Lefeuvre et al. (2008), and the proposed Global Lightning Mapper on board a NOAA GOES geostationary satellite which is due to be launched in 2012 will provide new insights on the physics of lightning. On Mars, an instrument package for the investigation of atmospheric electricity and dust storms to the surface of the red planet is overdue (Aplin 2006). An instrument capable of measuring the electric field and the flux of charged particles has been developed for future in-situ measurements on Mars and other bodies of the solar system (Renno and Kok 2008). The future JUNO mission to Jupiter (to be launched in 2011) will provide further insights into the dynamics of the Jovian atmosphere by using instruments to determine the water content and to derive further physical characteristics of the atmosphere down to a pressure level of about 100 bar. An optical camera as well as a plasma wave instrument are also able of detecting optical or radio emissions (whistlers) from lightning. At Saturn the current Cassini mission continues to monitor Saturn Electrostatic Discharges, and it searches for evidence of Titan lightning. A future mission to Titan could be in the form of a balloon, and Tokano and Lorenz (2006) simulated possible balloon trajectories. To our knowledge there are presently no definite plans to revisit the icy giants Uranus and Neptune.

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