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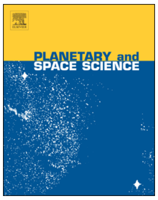

Storms on Venus: Lightning-induced chemistry and predicted products

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ABSTRACT

Observations by many spacecraft that have visited Venus over the last 40 years appear to confirm the presence of lightning storms in the Venus atmosphere. Recent observations by Venus Express indicate that lightning frequency and power is similar to that on Earth. While storms are occurring, energy deposition by lightning into Venus atmospheric constituents will immediately dissociate molecules into atoms, ions and plasma from the high temperatures in the lightning column ($>30{,}000$ K) and the associated shock waves and heating, after which these atom and ion fragments of C,O,S,N,H-containing molecules will recombine during cooldown to form new sets of molecules. Spark and discharge experiments in the literature suggest that lightning effects on the main atmospheric molecules CO_2, N_2, SO_2, H_2SO_4 and H_2O will yield carbon oxides and suboxides (CO_m, C_nO_m), sulfur oxides (S_nO, S_nO_m), oxygen (O_2), elemental sulfur (S_n), nitrogen oxides (NO, N_2O, NO_2), sulfuric acid clusters ($H_nS_mO_x^-$. $aH_nS_mO_x$ e.g. $HSO_4^-.mH_2SO_4$), polysulfur oxides, carbon soot and other exotic species. While the amounts generated in lightning storms would be much less than that derived from photochemistry, during storms these species can build up in a small area and so their local concentrations may increase significantly. For a storm of 100 × 100 km, the increase could be ~5 orders of magnitude if they remain in the storm region for a period before becoming well-mixed. Some of these molecular species may be detectable by instruments onboard Venus Express while they are concentrated in the storm regions. We explore the diversity of new products likely created in lightning storms on Venus.

1. Introduction

Lightning storms are a common occurrence in most planetary atmospheres. They are especially active on Earth, Jupiter, and Saturn and are likely also occurring on Uranus and Neptune (Borucki et al., 1982a, 1996; Dyudina et al., 2002, 2007, 2010; Fischer et al., 2006; Desch et al., 2002, Baines et al., 2006, 2007; Yair, 2008, 2012, Gibbard et al., 1999). On Venus, lightning has been inferred from observations by Venus Express and by earlier spacecraft such as Pioneer Venus and the Russian Venera missions (Krasnopolsky, 1983, Russell et al., 2006, 2007, 2008). Although studies of lightning have been conducted on every planet where it is confirmed, such as Earth, Jupiter, Saturn, Uranus and Neptune, relatively little has been done to characterize lightning storms on Venus or the high-temperature chemistry initiated by lightning. In this paper, chemical reactions and products expected to be occurring in lightning storms on Venus will be described. Earlier studies (Delitsky and Baines, 2012) showed that a suite of C,O,S,N,H-containing molecules are created and could be concentrated in storm regions with the enhancements possibly becoming temporarily detectable by ground-based and spacecraft observations. The expected concentrations produced by lightning are compared to the photochemical production of these species. In addition, estimates are given of their detectability by instruments onboard the Venus Express spacecraft now in orbit.

2. Spacecraft observations of Venus lightning

Many spacecraft that have visited Venus observed signs of lightning (Taylor et al., 1979, Ksanfomaliti, 1980, Russell et al., 2006, 2007). The Russian landers Venera 11, 12, 13 and 14 detected very low frequency waves during their descent to the surface. Venera 12 observed bursts of VLF as it descended and a short 8-sec burst at two frequencies upon landing. These bursty patterns are characteristic of atmospheric electromagnetic wave behavior generated by lightning.

Venera 9 made observations that appear to indicate optical detection of lightning storms. There were optical bursts of 0.25 second duration over a 70 second period, 100 flashes per second in a 50000 square km area near 32 degrees N latitude, and 120 flashes per minute over 1000 km^2. Power was 2.6×10^4 watt/Angstroms between 4500–7500 Angstroms and 3×10^7 J per burst in the visible,

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10^{10} J total energy in the intracloud lightning and a global rate of 45 km^{-2} yr^{-1} (Krasnopolsky, 1983).

In Pioneer Venus measurements, signals in the 30 kHz, 5.4 kHz, 730 Hz and 100 Hz narrowband filters indicated cloud-to-ionosphere lightning (Taylor et al., 1979, Russell et al., 2006). Cloud-to-ground discharges are considered to be very unlikely because the clouds on Venus are very high up, much higher than clouds on Earth and too high to create a potential for a discharge to go across. Thus, Venusian clouds are likely just too insulated from the surface for lightning to reach (Russell et al., 2011). The bottom of the ionosphere is much closer to the clouds, particularly in terms of the intervening column density of gas and so discharges upwards are more likely and should create a potential that would reach the electrical breakdown level and cause lightning discharges to occur (Russell et al., 2008).

Only one ground-based optical observation of lightning was reported for Venus (Hansell et al., 1995). This observation has not been repeated. This is intriguing especially since the discharges may propagate upward to the bottom of the ionosphere or are all intracloud and so theoretically should be visible.

Also observed were *whistlers*, electromagnetic waves guided by magnetic field lines (Yair et al., 2009). The Galileo spacecraft observed electromagnetic bursts during its flybys of Venus. The electric field power spectral density was plotted against frequency and the bursts at higher spectral density appear to be lightning (Russell et al., 2006).

Storms on Venus are most probably occurring in its cloud decks at altitudes from 40–80 km. The clouds are populated by two distinct types of aerosols: (1) visible-near-infrared (<3 μm) bright clouds comprised of predominantly 0.5–3.0-μm spherical particles of sulfuric acid (Hansen, 1969, Knollenberg and Hunten, 1980) and (2) UV-dark regions higher up comprised of an undetermined constituent. Recent results from Venus Express indicate that the UV absorber is located at and just above the mean cloudtop level near 60–65 km (Piccioni et al., 2012) and that lightning is prevalent within the clouds at a rate similar to that found on Earth (Russell et al., 2007, 2008).

In current observations, the MAG instrument onboard Venus Express detected frequent bursts indicating lightning (Russell et al., 2011). The flash rate was ~50/second, consistent with that from other spacecraft measurements (Russell et al., 2006, 2007, 2008).

3. Lightning characteristics

To understand Venus lightning, it is instructive to understand the characteristics of lightning on Earth. Lightning is a discharge of energy resulting from separation of charges (positive and negative) on particles in storm clouds over a large distance. This creates a potential that causes formation of an electric field. If an atmosphere of a planet is not very conductive, the field potential can grow very large and the possibility of an electric discharge in the form of lightning increases (Orville, 1968a, 1968b). Lightning discharges cause regions of the atmosphere to heat up to extremely high temperatures ($>30{,}000$ K) and create reactive plasmas for a short time (Orville, 1968a, 1968c). The great heat, shockwaves and electrons generated in a lightning storm will cause molecules to be dissociated into atoms, ions and radical fragments which recombine into new excited-state, neutral and ionic species.

On Earth, Jupiter, and Saturn (Dyudina et al., 2010, Baines et al., 2007, 2009), droplets of water in ice and liquid phases bumping against each other in convective currents is considered to be the prime source of charge separation. Venus has little water in its atmosphere; most of it is tied up in the sulfuric acid droplets in the cloud layers. However, charge separation may still occur from friction in sulfuric acid droplets in its clouds.

In Earth's atmosphere, ice or water particles can have positive or negative charges on them as they fall through the atmosphere. Initially, the minimal charges on falling droplets or ice particles are not sufficient to conduct current, that is, they are insulators (Ogawa, 1995). The droplets elongate as they fall in response to the ambient electric field. They can then break up due to inter-particle collisions and air resistance, which generates particles with multiple net charges. Once there is sufficient charge separation over a large altitude range, the potential seeks to neutralize the cloud, discharging in the form of a rapid flow of charged particles – lightning. At this point, the falling droplet becomes a conductor.

Filaments start to extend from the droplet caused by the electric potential. The bigger the water droplet, the less the electric field potential around it needs to be to initiate discharge (Ogawa, 1995). A water droplet of 1.2 mm radius requires an electric field of 1140 kV/m to produce filaments that lead to discharge, whereas a larger droplet of 2.5 mm radius requires only a field of 800 kV/m.

4. Lightning flash energy and temperature

A lightning discharge consists of a flash which lasts about 0.33 seconds and is made up of component lightning strokes of ~70 μs. (Orville, 1968a, 1968b, 1974). An average stroke contains ~2.5 coulombs of electrons ($\sim 1.56 \times 10^{19}$ electrons). The amount of charge that travels through a typical lightning bolt is ~15 coulombs, although larger bolts can be up to 350 coulombs (Hasbrouck, 1996). The path length of a cloud-to-ground lightning discharge can be ~10 km long; the lightning channel inside the core of the lightning column where chemistry occurs is ~10 cm in diameter (Orville 1974, Ogawa, 1995). Cloud-to-cloud lightning has shorter path lengths and is typically weaker than cloud-to-ground (Idone et al., 1984). The actual diameter where current is flowing is ~1 cm, but the surrounding area is lit up to ~10 cm diameter (the "luminous" diameter).

The reason the channel is luminous is because the air inside is *white-hot*. Temperatures can reach 20000–30000 K in the central core of the channel; the associated electron density is $\sim 1 \times 10^{24}$ e^{-}/m^3 (Orville, 1968b, 1968e, Ogawa, 1995, Orville et al., 1967b, 1974). The channel cools down very quickly, within microseconds. However, the slope of the temperature drop decreases and the temperature could stay at ~8000 K for many microseconds (see Orville (1968b) for a description and graphs of the change of temperature inside a lightning stroke volume as a function of time). A current of 10 Amps may be flowing which keeps the channel conductive (Brook et al., 1962). The channel pressure can exceed 10 atm (reaching 13 atm) at the core when the temperature is ~30000 K. This causes an outward pressure (shock wave) which devolves to the local atmospheric pressure in ~20 μs (Uman and Voshall, 1968). The electron count will drop until eventually the channel becomes nonconducting and the lightning stops. Air is nonconducting once the temperature drops below ~4000 K (Ogawa, 1995).

5. Lightning features

A lightning strike may have a power output of $\sim 10^{12}$ watts. Despite what they say, lightning *can* strike twice in the same place and in fact is much more likely to strike more than once down the conductivity channel established by the first stroke (Dwyer and Uman, 2014). Lightning travels down that channel of air again because it has been ionized on the first pass from cloud to ground or ionosphere and then this channel is the most conductive path available for the electrons the second time.

A downward stroke is followed by a more powerful upward stroke (the return stroke). The associated shock wave expands outward and can heat the surrounding air *outside* of the immediate channel to 2000–4000 K. As the air then cools very quickly, the ratios of products