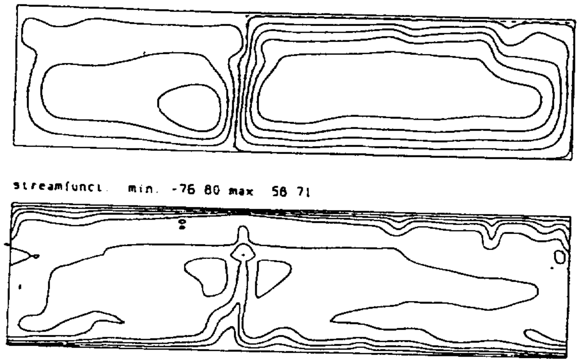

Fig. 2. Same diagram as Fig. 1, but at lower Rayleigh number (Ra = 2×10^6).

phase transitions. The olivine-spinel transition may give rise to secondary instabilities emanating from the thermal boundary layer, as it can be also observed in flows with both temperature- and pressure-dependent viscosity included.

As argued first by Kaula [4], the venusian mantle may contain much less water than the Earth's, resulting in a higher viscosity and therefore lower Rayleigh number. Our calculations confirm that lower Rayleigh number flows show less tendency to be layered (Fig. 2), as observed by Christensen and Yuen [2]. For terrestrial planets like Venus and Earth this means that the form of convection may undergo several changes during the planet's history. In early stages (characterized by high Rayleigh number) phase transitions act as a barrier to convective flows, resulting in low heat flows and cooling rates.

As the Rayleigh number decreases with time, the flow becomes more and more penetrative, the upper mantle heats up, and the lower mantle and core cool down, while heat flow increases despite the lower Rayleigh number. Due to the high cooling rate in this stage the vigor of convection decreases faster and the flow may undergo another transition from time dependent to steady state.

Thus the combined effects of a relatively dry venusian mantle and phase transition would facilitate the cooling of Venus in spite of its having a higher surface temperature. Venus is therefore in a stage of planetary evolution that is characterized by much less tectonic and volcanic activity. On the other hand, convection models with phase transitions [e.g.,5] and global seismic tomography suggest that the present-day Earth is in an earlier state of layered convection.

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EVIDENCE FOR LIGHTNING ON VENUS.

R. J. Strangeway, Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90024, USA.

Lightning is an interesting phenomenon both for atmospheric and ionospheric science. At the Earth lightning is generated in regions where there is strong convection. Lightning also requires the generation of large charge-separation electric fields. The energy dissipated in a lightning discharge can, for example, result in chemical reactions that would not normally occur. From an ionospheric point of view, lightning generates a broad spectrum of electromagnetic radiation. This radiation can propagate through the ionosphere as whistler mode waves, and at the Earth the waves propagate to high altitudes in the plasmasphere where they can cause energetic particle precipitation [1]. The atmosphere and ionosphere of Venus are quite different from at the Earth, and the presence of lightning at Venus has important consequences for our knowledge of why lightning occurs and how the energy is dissipated in the atmosphere and ionosphere.

As discussed here, it now appears that lightning occurs in the dusk local time sector at Venus. Since the clouds are at much higher altitudes at Venus than at the Earth, we expect lightning to be primarily an intracloud phenomenon [2]. It is possible, however, that lightning could also propagate upward into the ionosphere, as has been observed recently at the Earth [3]. This may explain the high-frequency VLF bursts detected at low altitudes in the nightside ionosphere by the Pioneer Venus Orbiter, as described below.

Some of the early evidence for lightning on Venus came from the Venera landers, which carried loop antennas to detect electromagnetic radiation in the VLF range [4]. These sensors detected sporadic impulsive signals. Since the detectors were sensitive to magnetic rather than electric field fluctuations, it is highly unlikely that these impulses were generated locally by the interaction of the lander and the atmosphere. An optical sensor was flown on Venera 9, and this instrument also detected occasional impulsive bursts [5].

The largest body of data used as evidence for lightning on Venus comes from the Pioneer Venus Orbiter electric field detector. This is a small plasma wave experiment that measures wave electric fields in the ELF and VLF range. Because of restrictions on power, weight, and telemetry, the instrument has only four frequency channels (100 Hz, 730 Hz, 5.4 kHz, and 30 kHz). Highly impulsive signals were detected at low altitudes in the nightside ionosphere in all four channels [6]. However, the ambient magnetic field at Venus is small, only a few tens of nanoteslas, and the electron gyrofrequency is usually less than 1 kHz, and often less than 500 Hz. Since there is a stop band for electromagnetic wave propagation between the electron gyrofrequency and plasma frequency, bursts detected in the higher channels do not correspond to freely propagating modes. In subsequent studies [7] F. L. Scarf and colleagues adopted a convention that bursts must be detected at only 100 Hz (i.e., below the gyrofrequency) for the bursts to be considered as lightning-generated whistlers. With this definition it was found that the signals tended to cluster over the highland regions [8], and Scarf and Russell speculated that the VLF bursts were whistler mode waves generated by lightning associated with volcanic activity. This was a highly controversial interpretation, which was subsequently criticized by H. A. Taylor and colleagues [9,10]. Among other criticisms, they pointed out that the studies of Scarf and colleagues were not normalized by the spacecraft dwell time, which tended to exaggerate the altitude dependence of the 100-Hz bursts. However, other studies [11] have shown that the burst rate does maximize at lowest altitudes. Nevertheless, it is important to note that the apparent geographic correlation may in fact be a consequence of the restricted longitudinal coverage of the Pioneer Venus Orbiter for each season of nightside periapsis. Periapsis in the early seasons was maintained at low altitudes, but was allowed to rise in later seasons. The periapsis longitude only covered the lowlands in these later seasons, and since the data were acquired at higher altitude, the event rate decreased. However, this decrease was mainly a consequence of the change in altitude, rather than a change in planetary longitude.

Although Scarf et al. only considered 100-Hz bursts as evidence for lightning, since these waves could be whistler mode, Russell et al. [12] also considered the high-frequency bursts as possible lightning events. They found that while the high-frequency events did show some longitudinal dependence, the data were better ordered by local time, with the peak rates occurring in the dusk local time sector. Consequently, it is now thought that the lightning is not associated with volcanic activity. Rather, it is due to weather processes in an analogous manner to lightning at the Earth, which tends to peak in afternoon local time sector [13].

The evidence for lightning at Venus from the VLF data now falls into two classes. The higher frequency bursts show the local time dependence, and the rate also decreases most quickly as a function of altitude [14]. These bursts are thought be a local response to the lightning discharge, and therefore are best suited for determining planetwide rates. The rates are found to be comparable to terrestrial rates. However, it is still not clear how the high-frequency signals enter the ionosphere. On the other hand, about 50% of the 100-Hz bursts are clearly whistler mode signals, as evidenced by the wave polarization [15]. These signals can propagate some distance in the surface ionosphere waveguide before entering the ionosphere. The 100-Hz bursts are therefore less reliable in determining the lightning rate, or the main source location.

Perhaps the least ambiguous evidence for lightning on Venus has come from the plasma wave data acquired by the Galileo spacecraft during the Venus flyby [16]. Unlike Pioneer Venus, Galileo was able to measure plasma waves at frequencies up to 500 kHz. The plasma wave experiment detected nine impulsive signals that were several standard deviations above the instrument background while the spacecraft was at a distance of about five planetary radii. Although some of the lower-frequency bursts could possibly have been Langmuir wave harmonics, the higher-frequency bursts were probably due to lightning. The bursts were at sufficiently high frequency to pass through the lower-density nightside ionosphere as freely propagating electromagnetic radiation.

While there is a strong body of evidence for the existence of lightning at Venus, there are still many questions that remain. From an ionospheric physics point of view, it is not clear how high-frequency signals can propagate through the ionosphere. The low-frequency signals do appear to be whistler mode waves, although there is still some doubt [17]. Also, although whistler mode propagation may be allowed locally, it is not necessarily certain that the waves can gain access to the ionosphere from below. For example, whistler mode propagation requires that the ambient magnetic field passes through the ionosphere into the atmosphere below. It is possible that the ionosphere completely shields out the magnetic field. With regard to atmospheric science, there are several questions that require further study. First, can charge separation occur in clouds at Venus? Is there sufficient atmospheric circulation to cause a local time dependence as observed in the VLF data? Do Venus clouds discharge to the ionosphere, and so cause strong local electromagnetic or electrostatic signals that could explain the high-frequency VLF bursts? While some of these questions may be answered as low-altitude data are acquired during the final entry phase of the Pioneer Venus Orbiter, many questions will still remain.

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VOLCANISM BY MELT-DRIVEN RAYLEIGH-TAYLOR INSTABILITIES AND POSSIBLE CONSEQUENCES OF MELTING FOR ADMITTANCE RATIOS ON VENUS.

P. J. Tackley[1], D. J. Stevenson[1], and D. R. Scott[2], [1]Division of Geological and Planetary Sciences, Caltech, Pasadena CA 91125, USA, [2]Department of Geological Sciences, University of Southern California, Los Angeles CA 90089, USA.

A large number of volcanic features exist on Venus, ranging from tens of thousands of small domes to large shields and coronae. It is difficult to reconcile all these with an explanation involving deep mantle plumes, since a number of separate arguments lead to the conclusion that deep mantle plumes reaching the base of the lithosphere must exceed a certain size. In addition, the fraction of basal heating in Venus' mantle may be significantly lower than in Earth's mantle, reducing the number of strong plumes from the core-mantle boundary. In three-dimensional convection simulations with mainly internal heating, weak, distributed upwellings are usually observed.

Description of Instability: We present an alternative mechanism for such volcanism, originally proposed for the Earth [1] and for Venus [2], involving Rayleigh-Taylor instabilities driven by melt buoyancy, occurring spontaneously in partially or incipiently molten regions. An adiabatically upwelling element of rock experiences pressure-release partial melting, hence increased buoyancy and upwelling velocity. This positive feedback situation can lead to an episode of melt buoyancy driven flow and magma production, with the melt percolating through the solid by Darcy flow. The percolation and loss of partial melt diminishes the buoyancy, leading to a maximum upwelling velocity at which melt percolation flux is equal to the rate of melt production by pressure-release melting.

Application to Venus: The instability has been thoroughly investigated and parameterized using finite-element numerical models, and hence its applicability to Venus can be assessed. Numerical convection simulations and theoretical considerations indicate that Venus' interior temperature is likely hotter than Earth's, hence the depth of intersection of the adiabat with the dry solidus may be appreciably deeper. In the regions of distributed broad-scale upwelling commonly observed in internally-heated convection simulations, partial melt may thus be generated by the adiabatically upwelling material, providing the necessary environment for these instabilities to develop. Scaling to realistic material properties and melting depths, the viscosity at shallow depth must be 10^{19} Pa.s or less, leading to a period of self-perpetuating circulation and magma production lasting $\sim$30 Ma, magma production rates of $\sim$1000 km^3/Ma, and lengthscales of $\sim$250 km.

Geoid, Topography, and Viscosity Profiles: Partial melt and buoyant residuum represent density anomalies that are of the same