Icarus 270 (2016) 30–36

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Detecting volcanism on Titan and Venus with microwave radiometry

Ralph D. Lorenz [a,*], Alice Le Gall [b], Michael A. Janssen [c]

[a] Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, USA
[b] Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS), Université de Versailles Saint-Quentin (UVSQ), Paris, France
[c] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

ARTICLE INFO

Article history:
Received 17 March 2015
Revised 7 July 2015
Accepted 10 July 2015
Available online 26 July 2015

Keywords:
Titan
Venus
Radio observations
Volcanism
Radiative transfer

ABSTRACT

The detection by spaceborne instrumentation of infrared thermal emission from volcanic eruptions is well-established on Earth, but is challenged on Venus and Titan by their optically-thick atmospheres. Microwave radiometry in principle offers the ability to detect emission from surface thermal anomalies on these worlds due to greater atmospheric transparency: microwaves also offer the prospect of sensing the shallow subsurface and thus may detect warmth from lava flows for longer than surface infrared emission. However, satellite microwave instruments typically have low spatial resolution (10s of km) so volcanic heat is diluted in the wide instrument footprint. We examine the prospects for the detection of volcanic deposits by microwave, given likely planetary eruption rates and lava flow deposit geometries, using Mt Etna as a template. Nondetection of prominent hotspots in Cassini data may imply that the resurfacing rate is lower than $\sim 2\ \mathrm{km}^3/\mathrm{yr}$, five times smaller than the expression of an Earth-like fraction of geothermal heat flow as latent heat in extrusive volcanism.

1. Introduction

The question of whether a planetary body is volcanically-active at the present epoch is of fundamental importance in understanding its evolution, and is of wide public interest as well (e.g. Smrekar et al., 2010; Shalygin et al., 2012). Apart from Earth, active volcanism is only known on Jupiter's moon Io, but evidence of relatively recent volcanism has been offered for Mars and Venus, and for Titan (e.g. Lopes et al., 2013).

Active volcanism on Io is detected optically and in the near-infrared where the glow of volcanic heat is unobstructed by an atmosphere, and surveillance of terrestrial volcanism is maintained by near-infrared monitoring from satellite platforms (e.g. Flynn et al., 2002). On Venus and Titan, optically-thick atmospheres and other factors challenge this approach, and so microwave sensing has been proposed as a means to detect 'hot spots' (e.g. Bondarenko et al., 2010; Lopes et al., 2013).

Unlike infrared sensing which probes only the top tens of microns, the radiance detected by a microwave radiometer over geological surfaces originates over a range of depths that may be centimeters to meters (e.g. Ulaby et al., 1981). The principal determinants of microwave transparency are liquid water content, and the amount of certain iron minerals: water ice well below the freezing point (so that no films of water are present) and dry silica sand are notably transparent materials.

Bondarenko et al. (2010) have suggested that microwave radiometry should be able to detect lava flows on Venus that are months–years old, by probing to depths where the lava is still hundreds of kelvin above ambient. Essentially the detectability of a buried lava flow relates to the ratio of the electrical skin depth (to which the instrument is sensitive) to the thermal skin depth (to which the lava has cooled).

Microwave radiometry has been suggested as a means of mapping lunar heat flow (e.g. Keihm and Langseth, 1975a,b; Keihm, 1984). The technique – essentially noting that longer wavelengths sense deeper, and thus that elevated brightness temperatures for longer wavelengths could be interpreted as a subsurface temperature gradient – relies on the attenuation being low enough that the temperature increment at the sensed depth is large enough to be detectable. The differential depth sensing with microwave wavelength in the lunar regolith is evident from the lack of a diurnal signal at longer wavelengths in the data from the multi-band radiometer on board Chang-E (e.g. Fa and Jin, 2010).

The ability of microwaves to sense the terrestrial subsurface is evident in locations where an absence of liquid water allows penetration to depth, for example, in the AMSR-E (Kawanishi et al., 2003) measurements of the seasonal variation of brightness temperature over the Dome-C site in Antarctica (e.g. Njoku et al., 2004). Whereas the 89 GHz brightness, penetrating only to shallow

---

* Corresponding author. Fax: +1 443 778 8939.
E-mail address: ralph.lorenz@jhuapl.edu (R.D. Lorenz).

http://dx.doi.org/10.1016/j.icarus.2015.07.023
0019-1035/

depths in the snow column, shows a pronounced (30 K) seasonal variation, the cycle is progressively-muted toward longer wavelengths which sense to depths where the seasonal temperature cycle is attenuated to about 12 K at 18 GHz and only ~3 K at 6.9 GHz.

The low-temperature icy surfaces of the outer Solar System moons similarly expose subsurface temperatures to microwave interrogation: recently Le Gall et al. (2014) analyzed Ku-band 2.2 cm microwave radiometer from Cassini to infer the presence of a seasonal temperature signature (whereas shallow-sensing thermal infrared sensing detects only a diurnal signature). Thus, while we are not aware of any reports of terrestrial remote detections of volcanic heat, the prospects for detecting extraterrestrial volcanism with microwave radiometry methods appear worth examining in detail.

2. Modeling approach

2.1. Thermal evolution and microwave remote sensing

For the purpose of assessing volcanic activity by microwave survey, we first assign a detection criterion. The measured property is the antenna temperature of the microwave instrument, which can be calibrated (taking instrumental and atmospheric effects into account) into a brightness temperature T_b averaged over the instrument footprint area F. Surface emissivity variations, instrumental noise and other effects cause variations, and a reliable detection with a low false alarm rate will have some threshold δ above the nominal surface temperature. Thus we detect a volcanic deposit if the emission temperature excess T_e over the volcanic deposit area A makes a contribution that exceeds this threshold.

Thus the detection criterion is

$$T_e \times \min(A/F, 1) > \delta$$

where the A/F term represents the geometric dilution of the signal when the deposit does not fill the instrument footprint, but is clamped to unity for cases where the deposit is larger than the footprint.

We express the deposit's temperature profile $T(z,t)$ where z is depth and t is time since deposition, and T is the excess above the ambient surface temperature T_s. For convenience we express the temperature history as a simple relaxation to zero with a cooling time constant C, which is estimated in the first instance as a simple conductive cooling time. This simple model ignores the latent heat in lava, as well as conduction into cold substrate overlain by the volcanic deposit (and, indeed the infiltration of rainfall, which can be important in the cooling of ignimbrites (e.g. Keating, 2005)), but uncertainties in these factors as well as in the other thermophysical properties are more conveniently bundled into a single parameter, which is readily compared with more elaborate models in any case. Similarly, as with many other models (see Appendix A) we consider Titan and Venus' thick atmospheres to efficiently pin the surface temperature of the lava to ambient, whereas due to finite flux heat transfer it must in fact be somewhat warmer. However, this is a less important consideration for microwave sounding at depth than for surface sensing in the near-infrared.

Thus we write the temperature excess above ambient $\Delta T(z,t)$ as a function of depth (z) and time (t)

$$\Delta T(z,t) = \Delta T_o \exp(-t/C(z)) \tag{1}$$

where ΔT_o is the initial excess (i.e. the lava temperature relative to ambient). or pure conductive cooling, $C(z) = z^2/\kappa$, where κ is the thermal diffusivity (i.e. thermal conductivity divided by the product of density and specific heat). Bondarenko et al. (2010) give values for Venus lavas of $\kappa \sim 0.25\text{–}1.2 \times 10^{-6}$ m^2/s, and suggest eruption temperatures of 1270–1900 K ($\Delta T_o \sim 500\text{–}1150$ K). For pure water ice at Titan surface conditions (at low temperature the conductivity of ice increases substantially to ~5 W/m/K, compared with a near-melting value of ~2, while the specific heat decreases to ~1000 J/kg/K), $\kappa \sim 5 \times 10^{-6}$ m^2/s; the eruption temperature would presumably be close to 273 K ($\Delta T_o \sim 180$ K, Titan's surface temperature being ~94 K).

In the event instead that the erupted material on Titan were ammonia–water eutectic, the eruption temperature would be 176 K (i.e. $\Delta T_o \sim 80$ K). On the other hand, the resultant ammonia dihydrate ice would have a rather lower thermal conductivity (e.g. Lorenz and Shandera, 2001) than pure water ice. Such dehydrate has appreciably different dielectric properties too – see later.

The effective brightness temperature excess of a surface corresponds to the following integral

$$\Delta T_e = E \int_0^{+\infty} K \Delta T(z) e^{-\tau(z)} dz \tag{2}$$

with

$$\tau = \int_0^{+z} K dz \tag{3}$$

and

$$K = (2\pi/\lambda)\sqrt{\varepsilon_r} \tan\delta \tag{4}$$

where λ is the wavelength, ε_r is the real part of the dielectric constant, and $\tan\delta$ is the loss tangent. The emissivity E at normal incidence is given (assuming a smooth surface) by

$$E = 1 - \left(\frac{\sqrt{\varepsilon_r} - 1}{\sqrt{\varepsilon_r} + 1}\right)^2 \tag{5}$$

Eq. (2) is readily computed as a function of the major parameters, but some overall properties are evident on inspection of the expressions above. In essence a significant temperature perturbation persists below some thermal skin depth, which varies as the square root of time and the thermal diffusivity. Meanwhile the remote sensing detects temperatures down to some electrical skin depth, which varies as the wavelength divided by the loss tangent. Thus low loss tangents (transparent material) allow the deepest, longest-lived perturbations to be sensed, and low thermal diffusivities allow temperature perturbations to persist nearest the surface.

This approach, using a single value for the loss tangent, is somewhat simplified in that loss tangents tend to increase substantially toward the melting point. This is well-known for ice, but also occurs for rocks (e.g. Presnall et al., 1972), and is in fact instrumental in a 'thermal runaway' effect encountered in microwave thermal processing of basalt (e.g. Jerby et al., 2002). Thus a lava flow being interrogated by radiometry will in fact become progressively more opaque near the melting level, such that fully molten temperatures may in fact never be observed even if the flow is molten at depth. On the other hand, we do not consider the enhanced high-temperature longevity of a flow due to the latent heat of any molten component, so our overall approach represents a good balance of fidelity and simplicity (see Appendix A).

The expressions above assume nadir observation of a smooth surface, and thus polarization can be neglected. More generally, this is not the case and observations must be corrected for the incidence angle and polarization. Sub-wavelength scale roughness see e.g. Choudhury et al. (1979) and volume scattering can be important factors, and careful modeling is required (e.g. Arvidson et al., 1994) to detect a thermal anomaly in a single observation (repeat-pass change detection is of course more straightforward) (see Fig. 1).

While detection of a brightness temperature in excess of the physical temperature expected for the surface can in principle be