Seeing Through the Atmosphere of Venus: What's on the Surface?

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Abstract

The exploration of the surface geology of Venus has been hampered by its inhospitable conditions and thick and opaque atmosphere. Fundamental properties, such as crustal composition and heterogeneity remain poorly constrained. Multiple analytical techniques are required to better understand its geology. A spectroscopy-based study laboratory study of the emissivity properties of Venus-relevant igneous rocks, measured at 440 °C by Dyar et al. (2020b; https://doi.org/10.1029/2020GL090497) shows that the use of multiple atmospheric windows in the 1-μm region can provide strong constraints on the FeO content of Venus-relevant igneous rocks, and by extension, the type of igneous rock. These results will improve our ability to map the surface geology of Venus remotely.

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13   **Key points:**
14   • Venus surface mapping can be advanced using near-infrared atmospheric windows
15   • Machine learning and laboratory spectra can help to quantify surface composition

16

17   **Index Terms**
18   6295 Venus
19   1027composition of the planets
20   1065 major and trace element geochemistry
21   1942 machine learning
22   8485 remote sensing of volcanoes

23

24   **Keywords**
25   Venus, VNIR, geology, basalt, igneous

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30 conditions and thick and opaque atmosphere. Fundamental properties, such as crustal
31 composition and heterogeneity remain poorly constrained. Multiple analytical techniques are
32 required to better understand its geology. A spectroscopy-based study laboratory study of the
33 emissivity properties of Venus-relevant igneous rocks, measured at 440 °C by Dyar et al.
34 (2020b; https://doi.org/10.1029/2020GL090497) shows that the use of multiple atmospheric
35 windows in the 1-µm region can provide strong constraints on the FeO content of Venus-relevant
36 igneous rocks, and by extension, the type of igneous rock. These results will improve our ability
37 to map the surface geology of Venus remotely.

38 **Plain Language Summary**

39 The extreme conditions of Venus' atmosphere and surface make exploration by optical
40 techniques difficult. A few successful landed missions and radar observations have helped to
41 understand its surface, which appears to be volcanic in nature. In spite of Venus' global shroud
42 of clouds, some spectral "windows" exist, which are selected wavelengths where the atmosphere
43 and clouds become more transparent. These windows allow us to measure radiation coming off
44 the surface and differences in the intensity of this radiation can be related to variations in the iron
45 (FeO) content of different rocks, which also correlated with different types of volcanic rocks.

46 **Introduction**

47 Venus, in spite of being Earth's "twin" (closest planet in terms of size and distance from the
48 Earth), is relatively unexplored as compared to the next-closest planet to Earth, Mars. This is
49 largely due to its inhospitable nature – shrouding clouds that contain sulfuric acid (e.g., Hansen
50 and Hovenier, 1974), a dense atmosphere with crushing surface pressure (~93 bars versus 1 bar
51 on Earth), and a hot surface (~470 °C versus ~15 °C average on Earth).

52 **Knowledge of surface geology**

53 These factors have all impeded our exploration of Venus, and as a result, our knowledge of its
54 surface is limited. Its topography and geomorphological features are known globally from orbital
55 radar missions such as Magellan (Saunders et al., 1992) and Venera 15 and 16 (Barsukov et al.,
56 1986). These observations show that Venus has surface topography consistent with a once-active
57 active interior (e.g., volcanoes) and a possible relatively recent crustal resurfacing (Strom et al.,
58 1994). There is also some evidence that volcanism may be ongoing (Esposito, 1984; Stofan et
59 al., 2016). The surface of Venus includes highs and lows, and there is evidence of the operation
60 of some tectonic processes (Solomon et al., 1992; Nimmo and McKenzie, 1998), but there is no
61 strong evidence for the operation of global-scale Earth-like tectonic processes (Barsukov et al.,
62 1986), although this evidence may have been obliterated by the aforementioned crustal
63 resurfacing. Radar-based analysis of Venus topography can provide clues to surface composition
64 on the basis of properties such as surface topography, dielectric properties, and radar roughness
65 and backscatter (e.g., Brossier et al., 2020).

The surface composition of Venus is incompletely known and selective. To date, seven Russian landers have successfully landed and operated on the surface, in different types of terrains – mostly highlands and plains (**Figure 1**) - for long enough to provide compositional data: major rock-forming elemental abundances at three locations determined using X-ray fluorescence (Venera 13 and 14: Surkov et al. (1984); Vega 2: Surkov et al. (1986); **Table 1**), and abundances of radioactive elements (Th, U, and K) determined by gamma-ray spectroscopy at five locations (Venera 8, 9, and 10, and Vega 1 and 2; **Table 2**). The three more comprehensive surface analyses (**Table 1**), have similarities with silica-poor terrestrial rocks such as basalts-picrobasalts, and boninites/komatiites. However, the abundances of Th, U, and K indicate a more compositionally diverse crust (Table 2), with inferred compositions ranging from granitic to picritic (**Table 2**). In addition to these analytical data, atmospheric radiogenic Ar has been used to constrain global properties such as mantle/crust composition and geological history (Kaula, 1999).

The images of the surface taken by the Venus landers show thin strata that are consistent with low-viscosity (e.g., basaltic) lava flows (Surkov et al., 1984; Ksanfomality, 2015). Measurements of their physical and mechanical properties indicate that the strata have friable, weakly-cemented porous structures (Surkov et al., 1986). The images also show a mixture of bedrock, cobbles, and finer-grained materials (Surkov et al., 1984).

Differences in surface conditions between Venus and Earth may affect surface properties such as weathering products (Gilmore et al., 2017). There are variations in radar backscatter properties with elevation that are consistent with differences in the composition and textures of erupted materials as well as altitude-dependent changes in weathering products (Garvin et al., 1985; Klose et al., 1992).

Interest in Venus has recently increased due to the recent putative discovery of phosphine (PH_3) in the Venusian atmosphere that is associated, on Earth, almost exclusively with biological processes (Greaves et al., 2020). This discovery coincides with, and may energize, new proposed missions to Venus including two NASA Discovery-class missions recently selected or more detailed study (https://www.nasa.gov/press-release/nasa-selects-four-possible-missions-to-study-the-secrets-of-the-solar-system), and the Roscomos Venera-D orbiter plus lander (Ivanov et al., 2017).

Optical spectroscopy for Venus surface exploration

In spite of Venus being a cloud-shrouded planet, there are a few narrow wavelength regions outside the visible range where it is possible to measure thermally-emitted radiation from lower altitudes (Allen and Crawford, 1984; Taylor et al., 1997). These include from the lower atmosphere near 1.74 and 2.34 µm (Crisp et al., 1989) and from the surface (around 1.02, 1.10, 1.18, 1.27, and 1.31 µm: Helbert et al., 2008; Kappel et al., 2016; Gilmore et al., 2017). A number of studies have found emissivity variations of up to 20% across the surface that are interpreted to be due to geological variations (e.g., Haus and Arnold, 2010; Gilmore et al., 2015; Mueller et al. 2020). Within these windows, it is also possible to determine whether any spectral structure, such as absorption bands, exist in VIRTIS data as each atmospheric window is covered

106   by multiple VIRTIS bands (e.g., Mueller et al., 2008). Measurements of emitted surface radiation
107   are only possible at night, when reflected light from Venus' clouds is not present.

108   The limited number of spectral windows can lead to problems of non-unique interpretations of
109   the spectra. Measured thermal emission spectra of the surface of Venus will be affected by
110   multiple factors, including atmospheric scattering and absorption, surface temperature,
111   emissivity, surface physical properties such as grain size, and composition (e.g., Adams and
112   Filice, 1967; Dyar et al., 2020b).

113   **Combining spectroscopy with other information**

114   Previous studies of Venus that utilize thermal emissions in the 1-µm region have also included
115   multiple types of observational data, laboratory spectra and modeling to try to constrain surface
116   composition. For instance, in the study by Mueller et al. (2008), they used measured flux at the
117   top of the atmosphere of Venus at 1.02, 1.10, and 1.18 µm, measured by the Venus Express
118   Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) as one data source to determine
119   surface composition. They discuss extensively the issues associated with deriving measurements
120   of emitted thermal radiation from the surface. They found that, as expected and consistent with
121   previous studies and expectations, the measured flux was positively correlated with surface
122   temperature and surface emissivity and that surface temperature was mainly a function of
123   elevation. After applying various corrections to account for viewing geometry, stray sunlight,
124   cloud opacity and topography, emissivity contrasts remained that were ascribed to variations in
125   surface emissivity (or unexpected temperature variations). Interpretation of the spectroscopic
126   data is predicated on the fact that felsic minerals have low emissivity at 1 µm while mafic
127   minerals tend toward higher emissivities. The emissivity variations were interpreted in the
128   context of radar data (geomorphology, dielectric properties, surface roughness), plausible models
129   of weathering, and to the landed missions compositional data (Kargel et al., 1993). These
130   variations were then interpreted as being indicative of variations in surface rock chemistry,
131   specifically differences in FeO content, which strongly affects emissivity (Hashimoto and Sugita,
132   2003; Helbert et al., 2020; Dyar et al., 2020a). Dyar et al. (2020a) also argued that the range of
133   emissivities seen on Venus was incompatible with a number of plausible basalt weathering
134   scenarios, suggesting that these emissivity variations are due to bulk mineralogical differences
135   across different terrains. Collectively, the observational data for Venus suggests rock types that
136   range from felsic to ultramafic (e.g., Surkov, 1983; Mueller et al., 2008; Gilmore et al., 2017;
137   Shellnutt, 2019).

138   The study by Dyar et al. (2020b) provides an important advance in using measurements of
139   emissivity from the surface of Venus to constrain surface composition. They examined six
140   spectral windows in the Venus atmosphere (0.86, 0.91, 0.99, 1.02, 1.11, and 1.18 µm) in the
141   context of a proposed Venus Emissivity Mapper that would image the surface in these band
142   passes on a future orbital mission. To determine the geological information content inherent in
143   six-band spectroscopy, they measured laboratory spectra of the saw-cut faces of slabs for a suite
144   of 18 plausible Venus rock types at a single temperature (440 °C). Based on the relationship
145   between FeO content, rock type, and emissivity (Helbert et al., 2020; Dyar et al., 2020b), they
146   found that wt.% FeO could be determined to an accuracy of ±2.47 wt.% for the full sample suite,

147 and ±0.42 - ±0.50 for sub-alkaline and alkali rocks, respectively. This relied on the application of
148 machine learning techniques, which also demonstrated that both long and short wavelength
149 bands (particularly the 0.86 μm) band) improved the regression results. The results of this study
150 translate into a high degree of confidence in being able to distinguish basalt from
151 granitic/rhyolitic rocks. In the future, they plan to explore the effects of possible confounding
152 factors, such as surface texture, alteration phases, porosity, and grain size.

153 **Summary and Future Prospects**

154 Optical remote sensing using Venus's atmospheric windows provides perhaps the only means to
155 determine surface composition (FeO content, rock type) remotely. It is complementary to other
156 remote sensing techniques such as radar, which is sensitive to different surface properties, such
157 as dielectric constants, and surface roughness. These two techniques also interrogate the surface
158 at different spatial scales, and together can reinforce each other to provide more robust
159 information about the surface of Venus.

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300

301 **Table 1. Composition of the Venus surface from previous Venus landers, versus selected terrestrial**
302 **igneous rocks**

Element/oxide (wt.%)	Venera-13	Venera-14	Vega-2	MORB[c]	Boninites/ Komatiites	Picrobasalt
305 SiO$_2$	45.1±3.0	48.7±3.6	45.6±3.2	49.21-50.93	47.2-55.9	38.69-50.63
306 TiO$_2$	1.59±0.45	1.25±0.41	0.2±0.1	1.19-1.77	0.20-0.52	0.79-2.99
307 Al$_2$O$_3$	15.8±3.0	17.9±2.6	16.0±1.8	14.86-17.25	1.3-10.3	7.77-14.26
308 FeO	9.3±2.2[a]	8.8±1.8[a]	7.74±1.1[a]	8.71-11.49[a]	4.9-10.0[a]	10.86-15.05[b]
309 MnO	0.2±0.1	0.16±0.08	0.14±0.12	0.16-0.17	0.14-0.20	0.30-0.35
310 MgO	11.4±6.2	8.1±3.3	11.5±3.7	7.10-8.53	4.6-13.0	13.22-18.90
311 CaO	7.1±0.96	10.3±1.2	7.5±0.7	11.14-11.86	5.1-10.1	9.62-13.53
312 K$_2$O	4.0±0.63	0.2±0.07	0.1±0.08	0.14-0.26	0.01-1.1	0.20-1.60
313 S	0.65±0.4	0.35±0.31	1.9±0.6	0.07-0.18	0.02-0.04	0-0.02
314 Cl	<0.3	<0.4	<0.3	0.002-0.21	0.04-0.12	0.02-0.03

315 [a] All Fe reported as FeO.
316 [b] Analyses include separate determination of Fe$_2$O$_3$.
317 [c] MORB = mid-ocean ridge basalts.
318 Sources: Venera-13 and Venera-14: Surkov et al. (1984); Vega-2: Surkov et al. (1986); MORB: Basaltic
319 Volcanism Study Project (1981); Moore and Schilling (1973); Labidi et al. (2014); boninites/komatiites:
320 Cameron et al. (1979); Li and Ripley (2009); Asafov et al. (2018); picrobasalts: Badredinov et al. (2018);
321 Kohut et al. (2006).
322 Additional comparative rock types can be found in Shellnutt (2019).
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325 **Table 2.** Potassium, uranium, and thorium concentrations measured on the surface of Venus
326

Mission	Potassium (%)	Uranium (10^{-4}%)	Thorium (10^{-4}%)	Inferred rock type
328 3Venera 8[a]	4.0±1.2	2.2±0.7	6.5±0.2	acid magmatic rocks; silicic
329 4Venera 9[b]	0.47±0.08	0.60±0.16	3.65±0.42	tholeiitic/alkaline basalt
330 4Venera 10[b]	0.30±0.16	0.46±0.26	0.70±0.34	tholeiitic/alkaline basalt
331 1Venera 13[c]	4.0±0.6 K$_2$O	n.d.	n.d.	mafic, alkaline
332 1Venera 14[c]	0.2±0.07 K$_2$O	n.d.	n.d.	MORB-like
333 2Vega 1[d]	0.45±0.22	0.64±0.47	1.5±1.2	tholeiitic basalt/gabbro
334 2Vega 2[d]	0.40±0.20	0.68±0.39	2.0±1.0	tholeiitic basalt/gabbro

335 [a] Vinogradov et al. (1973)
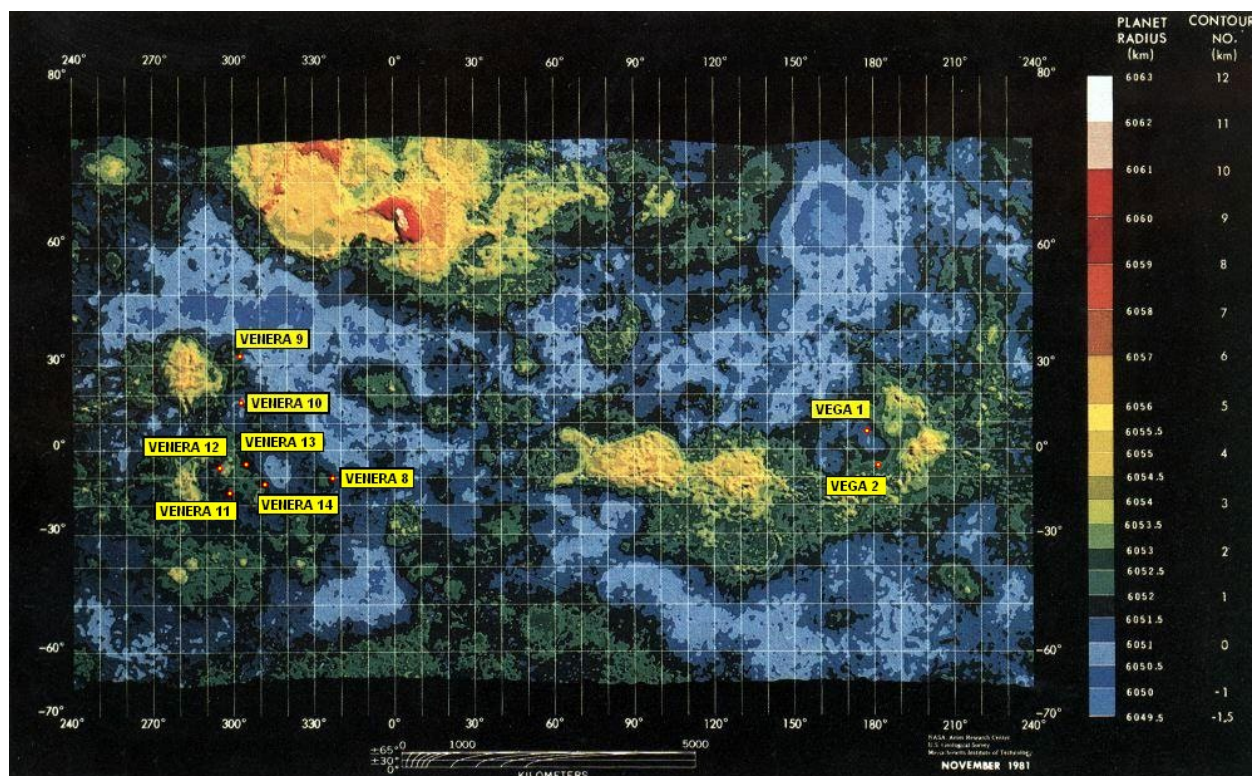336 [b] Florensky et al. (1977)
337 [c] Surkov et al. (1984)
338 [d] Surkov et al. (1987)
339
340

Figure 1. Location of Venus landed missions
(https://commons.wikimedia.org/w/index.php?curid=2051774).