THE EXPLORATION OF VENUS: CURRENT UNDERSTANDING AND OPEN QUESTIONS. Paul K. Byrne[1], Richard C. Ghail[2], Martha S. Gilmore[3], Suzanne E. Smrekar[4], Allan H. Treiman[5], Colin F. Wilson[6], and Sean C. Solomon[7], [1]Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA (paul.byrne@ncsu.edu), [2]Department of Earth Sciences, Royal Holloway, University of London, Surrey, TW20 OEX, UK, [3]Earth and Environmental Sciences Department, Wesleyan University, Middletown, CT 06459, USA, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, [5]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX 7705, USA, [6]Department of Atmospheric, Oceanic and Planetary Physics, Oxford University, Oxford, OX1 3PU, UK, and [7]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA.

Introduction: The successful exploration by robotic spacecraft of Venus began in August 1962 with the launch of NASA's Mariner 2, one month before John F. Kennedy's impassioned "We choose to go to the Moon" speech at Rice University. A flotilla of dedicated flyby, orbiter, probe, and lander missions followed over the next several decades, but only two spacecraft have been dedicated to Venus since the last U.S. mission to the planet, Magellan, was launched in May 1989—the ESA orbiter Venus Express in 2005 and the JAXA orbiter Akatsuki in 2010. The exploration of the second planet has not therefore kept pace since the mid-1990s with similar efforts for Mars, the Moon, or Mercury, even as Venus has come to be seen as a potential analog to an early Earth [1] and as a means by which to understand Earth-size exoplanets [2]. We review the current state of understanding of the Venus atmosphere, surface, and interior revealed by nearly six decades of spacecraft exploration, and we briefly discuss a few of the major questions for Venus science yet to be addressed.

Venus from Afar: To a distant observer, Venus appears as a rocky planet similar in size to Earth (0.82 $M_\oplus$ [3], 0.95 $r_\oplus$ [4]), situated about 0.72 AU from the Sun (and thus within the Solar System's habitable zone [5]), and hosting a dense atmosphere and a global cloud cover that obscures the surface at visible wavelengths. Measurements from Earth with the Goldstone antenna confirmed that Venus has a retrograde rotation [6], and observations made by Mariner 2 indicated high temperatures in the lower atmosphere [7] and no resolvable global magnetic field [8]. Venus has neither a ring system nor any moons.

The Venus Atmosphere: The Soviet Venera 4 probe returned the first in situ measurements of the dense Venus atmosphere, showing its high surface pressure [8], a composition dominated by CO_2 with negligible water vapor [9], and temperatures thought to be the result of a runaway greenhouse [9,10]. The Venera 8 spacecraft established the altitude of the global cloud layer as tens of kilometers above the surface [11], composed primarily of H_2SO_4, probably formed from H_2O and SO_2 [e.g., 12]. High D/H ratios were reported in the Venus atmosphere by the Mariner 5 spacecraft during its flyby of the planet [13], a finding later confirmed by the NASA Pioneer Venus probe [14] and indicative of the loss of substantial atmospheric water [e.g., 15,16]. Pioneer Venus also found that Venus has outgassed much less Ar than Earth [17], possibly the result of a history of less melting or mantle overturn than its larger neighbor [e.g., 18]. Later, the Soviet Vega 1 and 2 balloons measured highly variable atmospheric conditions as they traversed several thousand kilometers in Venus's middle cloud layer [19]. Upon its arrival in 2005, the Venus Express orbiter provided new insight into the planet's atmosphere, including an improved characterization of the upper cloud layer [20], evidence for polar vortices [21], confirmation of lightning [22], and even evidence of recent volcanic activity [23]. Notable results from the Akatsuki orbiter, still operating at Venus at time of writing, include the discovery of a large gravity wave at the cloud-top level arising from atmosphere–topography interaction [24].

The Venus Surface: Venera 8 was the first spacecraft to land successfully on the Venus surface, and it confirmed earlier measurements of surface temperature and pressure (~740 K, ~9.3 MPa) [25]; the mission also returned compositional data from the landing site pointing to a silicic rock type at that site [26]. Alkaline and tholeiitic basaltic compositions, respectively, were found at landing sites of the Soviet Venera 13 and 14 missions [27], suggesting that much of the surface of Venus is predominantly basaltic, although the Vega 2 lander measurements pointed to an anorthosite–norite–troctolite composition at its landing site [28]. These data indicated that the second planet is differentiated [26], likely with a crust, mantle, and core (albeit without a core dynamo). These landers also returned color images from the surface, revealing a landscape of thinly stratified rocks consistent with lithified accumulations of volcanic ash or sediment [29].

The Venera 15 and 16 orbiters imaged the surface with cloud-penetrating radar, finding evidence for extensive tectonic deformation and widespread volcanic deposits, and permitting the identification of major surface units, including smooth plains and the enigmatic, highly deformed tessera terrains [30,31]. But our understanding of the planet's surface was markedly enhanced by the Magellan spacecraft, inserted into orbit about Venus in 1990. Magellan ultimately returned the first high-resolution (~75 m/pixel) global radar image mosaic of the planet, as well as altimetric and emissivity datasets [e.g., 32], and showed Venus to be a world with a vast array of distributed and concentrated tectonic and volcanotectonic structures [33,34], abundant evidence for intrusive and extrusive activity [35], and a dearth of impact craters less than 25 km in diameter and none less than 3 km across [36]. Indeed, crater statistics derived from global Magellan data yield an average model age for the surface of 700–800 Myr [37], with global-scale volcanic resurfacing likely the dominant reason for such apparent youth [38]. The paucity of craters strongly challenges efforts to determine surface retention ages on the scales of individual geological units and has led to disagreement as to whether the global crater population is random [e.g., 38] or merely apparently so [e.g., 39]. As one result, there have been strongly differing views of the planet's geological history, from catastrophic [e.g., 40] or episodic [e.g., 41] burial, to equilibrium or steady-state volcanic resurfacing [e.g., 42], to secular variations in resurfacing style [e.g., 43,44], as well as interpretations involving systematic changes in volcanic and tectonic activity with time [e.g., 45] and ones with no such "directional" changes [e.g., 46].

Nonetheless, Magellan enabled the near-global mapping and characterization of surface units on the planet [47] and, although affirming that Earth-style plate tectonics does not operate on Venus [33], has shown Venus to be a world broadly organized into a set of elevated rift systems and associated coronae, low-lying basins, and continent-like highlands. Moreover, Magellan radar data have provided widespread evidence for continental-style lateral motion of crustal blocks—in most cases limited in extent [48] but with larger displacements at Lakshmi Planum [49] and some tessera plateaus [50]—and even roll-back subduction of lithosphere around some coronae [51]. And changes in radar backscatter with elevation imply that surface–atmosphere interactions are important, yielding new mineral phases [52] and heavy metal frosts [53].

The Venus Interior: On the basis of Earth analogy, Venus likely has a peridotite mantle [54]. Gravity and topography data from Pioneer Venus, Venera 15 and 16, and Magellan together indicate that highland terrains appear to be isostatically compensated (e.g., by thicker than average crust), that the low-lying plains are characterized by geoid lows sufficiently strong to imply compensation within the mantle (e.g., by mantle downwelling), and that the elongate regions of higher terrain with rift systems, volcanic landforms, and strong positive geoid and gravity anomalies that punctuate those plains also require deep compensation (e.g., by mantle upwelling and likely recent melt formation, ascent, and eruption) [33,55,56]. And, from fits of topography across rift systems, Venus may possess an active subcrustal lid rejuvenation regime today [57].

What's Next for Venus Exploration? Our current view of Venus has benefitted from an early phase of sustained exploration, but new data are required to take the next steps in tackling outstanding questions. What conditions characterized ancient Venus [58]? How did the Venus surface evolve to its present state, and when? To what extent is Venus geologically active today? What can Venus tell us of early Earth, and of the fate that awaits our planet? And how representative is Venus of Earth-size planets in orbit about other stars? Substantial advances in instrument design since Magellan mean that these questions can be addressed anew [59]. Most generally, the exploration of Venus so far tells us that, if we are to understand our own world as we view our planetary neighbors in this star system and beyond, we must return to our sister planet.

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