



What is the Oxygen Isotope Composition of Venus? The Scientific Case for Sample Return from Earth's “Sister” Planet

Richard C. Greenwood¹ · Mahesh Anand^{1,2}

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Abstract Venus is Earth's closest planetary neighbour and both bodies are of similar size and mass. As a consequence, Venus is often described as Earth's sister planet. But the two worlds have followed very different evolutionary paths, with Earth having benign surface conditions, whereas Venus has a surface temperature of 464 °C and a surface pressure of 92 bar. These inhospitable surface conditions may partially explain why there has been such a dearth of space missions to Venus in recent years.

The oxygen isotope composition of Venus is currently unknown. However, this single measurement ($\Delta^{17}\text{O}$) would have first order implications for our understanding of how large terrestrial planets are built. Recent isotopic studies indicate that the Solar System is bimodal in composition, divided into a carbonaceous chondrite (CC) group and a non-carbonaceous (NC) group. The CC group probably originated in the outer Solar System and the NC group in the inner Solar System. Venus comprises 41% by mass of the inner Solar System compared to 50% for Earth and only 5% for Mars. Models for building large terrestrial planets, such as Earth and Venus, would be significantly improved by a determination of the $\Delta^{17}\text{O}$ composition of a returned sample from Venus. This measurement would help constrain the extent of early inner Solar System isotopic homogenisation and help to identify whether the feeding zones of the terrestrial planets were narrow or wide.

Determining the $\Delta^{17}\text{O}$ composition of Venus would also have significant implications for our understanding of how the Moon formed. Recent lunar formation models invoke a high energy impact between the proto-Earth and an inner Solar System-derived impactor body, Theia. The close isotopic similarity between the Earth and Moon is explained by these models as being a consequence of high-temperature, post-impact mixing. However, if

Role of Sample Return in Addressing Major Questions in Planetary Sciences

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✉ R.C. Greenwood
r.c.greenwood@open.ac.uk

¹ Planetary and Space Sciences, School of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

² Department of Earth Sciences, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK

Earth and Venus proved to be isotopic clones with respect to $\Delta^{17}\text{O}$, this would favour the classic, lower energy, giant impact scenario.

We review the surface geology of Venus with the aim of identifying potential terrains that could be targeted by a robotic sample return mission. While the potentially ancient tessera terrains would be of great scientific interest, the need to minimise the influence of venusian weathering favours the sampling of young basaltic plains. In terms of a nominal sample mass, 10 g would be sufficient to undertake a full range of geochemical, isotopic and dating studies. However, it is important that additional material is collected as a legacy sample. As a consequence, a returned sample mass of at least 100 g should be recovered.

Two scenarios for robotic sample return missions from Venus are presented, based on previous mission proposals. The most cost effective approach involves a “Grab and Go” strategy, either using a lander and separate orbiter, or possibly just a stand-alone lander. Sample return could also be achieved as part of a more ambitious, extended mission to study the venusian atmosphere. In both scenarios it is critical to obtain a surface atmospheric sample to define the extent of atmosphere-lithosphere oxygen isotopic disequilibrium. Surface sampling would be carried out by multiple techniques (drill, scoop, “vacuum-cleaner” device) to ensure success. Surface operations would take no longer than one hour.

Analysis of returned samples would provide a firm basis for assessing similarities and differences between the evolution of Venus, Earth, Mars and smaller bodies such as Vesta. The Solar System provides an important case study in how two almost identical bodies, Earth and Venus, could have had such a divergent evolution. Finally, Venus, with its runaway greenhouse atmosphere, may provide data relevant to the understanding of similar less extreme processes on Earth. Venus is Earth’s planetary twin and deserves to be better studied and understood. In a wider context, analysis of returned samples from Venus would provide data relevant to the study of exoplanetary systems.

Keywords Venus · Sample return · Oxygen isotopes · Planetary protection · Exoplanets · Mars · Moon · Giant impact · Grab and Go · Bimodal Solar System · Inner Solar System · Tessera terrains

1 Introduction

1.1 Earth’s Twin Sister?

Venus (Fig. 1) is often viewed as Earth’s sister planet, or perhaps more accurately its ugly sister. This familial comparison stems from their approximately equal mass and physical size (Taylor et al. 2018). But compared to the relatively benign and hospitable surface conditions that prevail on Earth, Venus is the stuff of nightmares. The planet has a surface temperature of 464 °C (Williams 2018a), sufficient to melt lead, tin and zinc! Its broiling atmosphere is composed principally of carbon dioxide (96.5%), with a minor amount of nitrogen (3.5%) and only a trace of water vapour (0.002%). The pressure at the surface is a spacecraft crushing 92 bars. To add to this hellish vision, its deep, thick clouds are composed principally of sulphuric acid, mixed with water (approx. 85% H_2SO_4 ; 15% H_2O) (Titov et al. 2018).

At least in terms of the prevailing surface conditions, Venus appears to be a dead, uninhabitable world. From a human perspective, it is widely perceived to be an apocalyptic warning about the ultimate consequences of a runaway greenhouse effect (Leconte et al. 2014). Apart from speculative science fiction-style scenarios, no serious space agency plans



Fig. 1 Global view of the surface of Venus constructed from Magellan synthetic aperture radar mosaics and Pioneer Venus Orbiter data. Simulated colour used to enhance small-scale structure. Image produced by the Solar System Visualization project and the Magellan science team JPL. (Image credit: NASA/JPL)

exist to land humans on the surface of Venus (Taylor 2014), in sharp contrast to NASA's long term strategic goal for Mars (National Space Policy 2010).

Venus is Earth's nearest planetary neighbour, being 38.2 million kilometres away at their closest approach, compared with 55.7 million kilometres for Earth and Mars (Williams 2018a, 2018b). This proximity makes space travel to Venus slightly shorter than to Mars, such that the European Space Agency's (ESA) Venus Express spacecraft took 153 days to arrive at its destination, compared to 201 days for Mars Express. Historically, Venus and Mars have received similar levels of attention from international space agencies, with both being targeted by 47 spacecraft (Williams 2020a, 2020b). Taylor et al. (2018) estimate that about 60% of the probes sent to Venus have largely succeeded in their missions; a rate that is similar to that for Mars (Planetary Society 2020). There are eight active missions to the red planet and only one, Japan Aerospace Exploration Agency's (JAXA) Akatsuki orbiter (Nakamura et al. 2016), currently studying Venus. In addition, there are four imminent missions to Mars (ESA's Exo Mars Rover, National Aeronau-

tics and Space Administration's (NASA) Mars 2020 mission, Emirates Mars Mission, China Mars 2020). In contrast, there are currently no firm commitments from any international space agency to build a spacecraft to study Venus (Glaze and Garvin 2018; Glaze et al. 2018). However, this situation may be about to change. In May 2018 ESA selected the Venus orbiter mission EnVision (Ghail et al. 2017) as one of three finalists for its medium-class M5 Cosmic Vision programme. Final selection is due in 2021, with a possible launch in 2032. Two of the four missions selected in February 2019 for further evaluation as part of the NASA Discovery Programme are Venus remote sensing missions: DAVINCI+ (Garvin et al. 2020) and VERITAS (Smrekar et al. 2019).

A renewed interest in Venus exploration is long overdue. The perception of Venus as a "pariah" planet does not stand up to closer scientific scrutiny. Thus, while Venus may currently be an uninhabitable world, the situation may have been very different in the relatively recent past. It has been suggested that Venus was once an Earth-like planet with oceans (Hashimoto et al. 2008) and that evidence of erosion by flowing liquid water remains detectable on surface rocks (Khawja et al. 2020). This interpretation is consistent with the proposal that Venus maintained a habitable climate until about 700 Myr ago (Way et al. 2016). There is also the potential possibility that life may still be present on Venus within the cloud deck, at altitudes of between 51 and 62 km (Dartnell et al. 2015).

There is a growing recognition that developing realistic models for the long-term climatic and geological evolution of Venus will help to improve our understanding of why the Earth has remained habitable for most its existence (e.g. Driscoll and Bercovici 2013; Kodama et al. 2019), despite a progressive increase in solar energy input; an issue generally referred to as the "faint young Sun paradox" (Feulner 2012). The luminosity of the Sun will continue to increase in the future, with stark, albeit very long-term, implications for Earth's habitability (Wolf and Toon 2014). At some stage in its later evolution the Earth may have a climate that resembles present day Venus. The proximity of Earth and Venus and their apparent climatic dichotomy may be just that, "apparent". Venus could simply be at a more advanced stage on an evolutionary route that Earth will one day follow. While this is little more than speculation, it is certainly the case that the study of Venus has implications for our understanding of terrestrial planet evolution in its widest sense (Wilson et al. 2019). A related scientific development has been the recognition that understanding the different evolutionary paths of Earth and Venus has important implications for the search for habitable, Earth-like exoplanets (Angelo et al. 2017; Kane et al. 2018, 2019).

1.2 The Scientific Case for Sample Return from Venus

Space exploration is by its very nature a hugely expensive enterprise. In order to justify the very large sums of public money that are necessarily involved, it is important that the scientific objectives of any space mission are of primary significance. Here we argue that a sample return mission to the surface of Venus, despite the significant costs involved, represents an urgent and first-order scientific challenge. What is at stake is our understanding of how the Solar System formed and the mechanism by which the planets, particularly the inner terrestrial planets, including our own, accreted and evolved. At the heart of the scientific case is the question posed by the title of this article, namely: What is the oxygen isotope composition of Venus?

We are far from being the first to suggest that sample return from Venus would be a high priority scientific objective (Rodgers et al. 2000; Basilevsky et al. 2007; Stevenson and Halliday 2014). In 2014, The Royal Society convened an international discussion meeting entitled Origin of the Moon. In the published overview of the meeting, Stevenson and

Table 1 Mass of inner Solar System bodies

	Mass (kg)	%
Mercury	3.30×10^{23}	2.78
Venus	4.87×10^{24}	40.97
Earth	5.97×10^{24}	50.22
Moon	7.35×10^{22}	0.62
Mars	6.41×10^{23}	5.39
Asteroid belt	2.30×10^{21}	0.02
Total	1.19×10^{25}	100.00

Data Sources: Planetary Fact Sheet (Williams 2019a); Asteroid Fact Sheet (Williams 2019b)

Halliday (2014) stated: “One question that recurred during discussion at the Royal Society conference on ‘The Origin of the Moon’ was that of what single piece of information the speakers would want to know to move the science forward. A recurring answer was the composition of Venus. It would tell us if the Earth and Moon are unusual in being so similar isotopically.”

Table 1 demonstrates why speakers at The Royal Society conference were so keen to obtain samples from Venus. Excluding material from our own planet, we currently have samples from Mars, the Moon and the asteroid belt (McSween 1994; Udry et al. 2019; Greenwood et al. 2020; Ireland et al. 2020). However, these bodies represent little more than 6% of the mass of the inner Solar System. If you include Earth that jumps to just over 56%. But with a returned sample from Venus we would have material from bodies that represent over 97% of the inner Solar System’s mass. As discussed later in this article, a venusian sample would almost certainly transform our understanding of how the inner Solar System was built. This could be put another way. If sample return was based solely on how representative a body was of the inner Solar System, would we choose to go first to Mars (5.4% relative mass) or Venus (41% relative mass)? Of course we are going to Mars for reasons other than its rather diminutive size, which is just as well. However, as we attempt to demonstrate in this article, there are also very compelling reasons why we should not ignore Venus (Glaze and Garvin 2018).

It is perhaps surprising that more effort and resources are not currently being expended trying to understand the formation and early evolution of our “twin” planet. As we discuss in later sections, each new discovery about Venus has implications for our Earth. The absence of plate tectonics, or lack of a global magnetosphere are puzzling in a planet which is roughly the same size and composition as Earth (Wilson et al. 2019). Venus has an atmosphere, but it is nothing like ours. A runaway greenhouse effect on Venus is a troubling reminder that our own atmosphere may be heating up, only in our case human activity is at least partially to blame. Are we heading in the same direction as Venus? Research on Venus has a compare and contrast feel about it! Venus may be a nightmare world, but we ignore it at our peril (Goldblatt and Watson 2012).

Retrieving material from the surface of Venus and returning it to Earth is not just technically feasible, but in many cases important components for such a mission have already been tested successfully, either directly in the venusian environment, or under simulated conditions (Rodgers et al. 2000; Rehnmark et al. 2017; Shibata et al. 2017; Glaze et al. 2018; Wilson et al. 2019). We discuss here, not only the overwhelming scientific case for a sample return mission to Venus, but also outline various practical scenarios for achieving this goal on a realistic timescale and at a cost that is no greater than currently funded missions to Mars.

In the first part of this article we look at why essentially a single measurement of the bulk oxygen isotope composition of Venus is of critical importance in understanding the formation and early evolution of the Solar System. We then review some key features of Venus, including its surficial geology, with the aim of defining areas which might potentially be favourable for sample recovery. Next, we consider possible configurations for a sample return mission. Finally, we review the range of analytical techniques that could be applied to the characterisation and analysis of these precious extraterrestrial materials once they have been brought back to Earth.

2 Why is an Oxygen Isotope Analysis of Venus so Important?

2.1 What's so Great About Oxygen?

Spectroscopic measurements of the solar photosphere show that oxygen is the third most abundant element in the Solar System, after hydrogen and helium (Lodders 2003). Of equal importance, from the perspective of planetary formation processes, is that oxygen is a major mineral-forming element and makes up nearly 46 wt.% of the Bulk Silicate Earth (Javoy et al. 2010). All the current indications are that Venus has essentially the same bulk composition as the Earth (Treiman 2009). In addition to its Solar System and Bulk-Earth abundances, a further critical feature of oxygen is the fact that it readily combines with hydrogen to form water. Water played an essential role in the evolution of early life (Nisbet and Sleep 2001), is widespread throughout the Solar System (Raymond and Izidoro 2017), and experiments indicate that it may have promoted the fast accretion of early planetary bodies by helping dust grains stick together (Gundlach and Blum 2015). It has been shown that a significant proportion of the water in the Solar System was inherited from its parent molecular cloud (Cleeves et al. 2014).

2.2 Oxygen Isotopes – Notation

Oxygen has three stable isotopes: ^{16}O , ^{17}O , ^{18}O , with average terrestrial abundances of 99.757%, 0.038% and 0.205% respectively (Rosman and Taylor 1998). For analytical reasons, absolute abundances of the three isotopes are not generally measured and instead compositions are determined as isotope ratios ($^{17}\text{O}/^{16}\text{O}$ and $^{18}\text{O}/^{16}\text{O}$) (Ireland et al. 2020). Oxygen isotopic analyses are generally reported in standard δ notation, where $\delta^{18}\text{O}$ is calculated relative to the international standard Vienna Standard Mean Ocean Water (VSMOW) as $\delta^{18}\text{O} = [(^{18}\text{O}/^{16}\text{O}_{\text{sample}})/(^{18}\text{O}/^{16}\text{O}_{\text{VSMOW}}) - 1] \times 1000$ (‰) and similarly for $\delta^{17}\text{O}$ using the $^{17}\text{O}/^{16}\text{O}$ ratio.

Oxygen is readily fractionated by a variety of chemical and physical processes, with the magnitude of this variation being a function of the masses of the isotopes and as a consequence is termed mass-dependent fractionation. Thus, for any particular process the $^{18}\text{O}/^{16}\text{O}$ ratio will vary by approximately twice as much as the $^{17}\text{O}/^{16}\text{O}$ ratio. When oxygen isotope analyses for terrestrial samples are plotted on a three-isotope diagram, with $\delta^{18}\text{O}$ plotted as the abscissa (Fig. 2), the resultant line of slope ~ 0.52 (Matsuhisa et al. 1978) is commonly referred to as the terrestrial fractionation line (TFL). Deviations from this reference line are conventionally expressed as: $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52\delta^{18}\text{O}$ (e.g. Clayton and Mayeda 1988). $\Delta^{17}\text{O}$ can be expressed more accurately using the linearized format of Miller (2002):

$$\Delta^{17}\text{O} = 1000 \ln(1 + \delta^{17}\text{O}/1000) - \lambda 1000 \ln(1 + \delta^{18}\text{O}/1000)$$

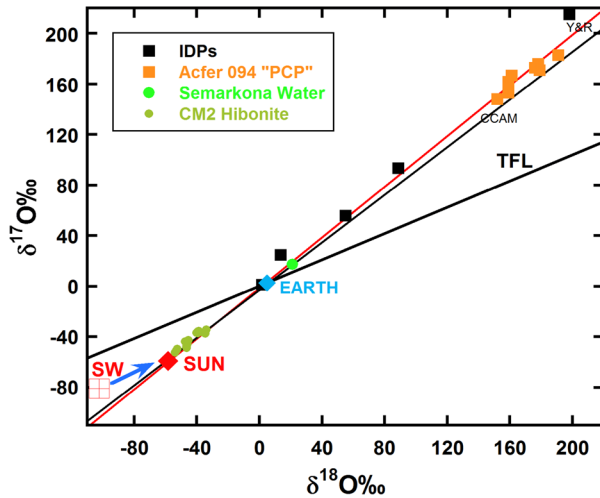


Fig. 2 Oxygen three-isotope plot showing the principal Solar System reservoirs. The diagram is essentially a mixing line between a ^{16}O -rich endmember (the Sun) and a more poorly constrained ^{16}O -poor endmember, as detected in the matrix of Acfer 094 (Sakamoto et al. 2007) and some IDPs (Starkey et al. 2014) and possibly reflecting the composition of primordial water (Sakamoto et al. 2007). The composition of the Sun is derived from Genesis solar wind (SW) measurements projected onto the CCAM line (McKeegan et al. 2011). Refractory solids (e.g. hibonite, corundum) have ^{16}O -rich compositions (Liu et al. 2009; Bodénan et al. 2014), consistent with formation from a gas of solar composition (Krot et al. 2009). Also shown is the inferred water composition from Semarkona (Choi et al. 1998). Mixing lines: CCAM (Clayton et al. 1977), Y&R (Young and Russell 1998)

Values for λ used in the literature for meteorites and related extraterrestrial samples vary between approximately 0.5247 and 0.5305 (Pack and Herwartz 2014; Greenwood et al. 2017; Miller et al. 2020).

2.3 High-Precision Oxygen Isotope Measurements – Sample Return or In Situ Analysis?

There are currently two principal laboratory techniques for oxygen isotope analysis of rocks and minerals: (i) infrared laser-assisted fluorination and (ii) secondary ion mass spectrometry (SIMS) (Greenwood et al. 2017; Ireland et al. 2020). Laser fluorination is a bulk technique and so unlike SIMS is not capable of spot analysis, however, it has the important advantage of achieving high levels of precision. Thus, based on repeat analysis of their internal obsidian standard ($n = 39$), Greenwood et al. (2018b) obtained the following precision: $\pm 0.05\text{‰}$ for $\delta^{17}\text{O}$; $\pm 0.09\text{‰}$ for $\delta^{18}\text{O}$, and $\pm 0.02\text{‰}$ for $\Delta^{17}\text{O}$ (2σ). At the present time and for the foreseeable future, this level of precision is unobtainable by instrumentation that can realistically be operated on a spacecraft. Amongst the highest levels of precision so far achieved for oxygen isotope analysis by in situ spacecraft measurements are those made by the Curiosity rover at Gale Crater using a tunable laser spectrometer (Webster et al. 2013). These measurements were made on atmospheric CO_2 and had the following precision: $\pm 5\text{‰}$ (2SEM) for $\delta^{17}\text{O}$ and $\pm 5\text{‰}$ (2SEM) for $\delta^{18}\text{O}$. Other oxygen isotope measurements made by spacecraft-based instruments generally have lower precision than those achieved by Curiosity (Alday et al. 2019). While these measurements represent significant scientific achievements, their precision is much lower than can be achieved by laboratory-based laser fluorination. As will be discussed later in this paper, there is a realistic possibility that Venus

will have a lithospheric $\Delta^{17}\text{O}$ composition that is extremely close to that of Earth's. An in situ analysis by a spacecraft-based instrument would not be capable of resolving such differences and instead sample return is the only viable option.

2.4 The Origin of Mass-Independent Oxygen Isotope Variation in Solar System Materials

The discovery by Clayton and co-workers (Clayton et al. 1973) that oxygen in carbonaceous chondrite meteorites, and its constituent high-temperature components, displays mass-independent variation was a major breakthrough in planetary sciences and provided cosmochemists with a powerful new tool to investigate early Solar System processes (Greenwood et al. 2017). Clayton et al. (1973) showed that rather than plotting on a mass fractionation line with a slope close to 0.5, carbonaceous chondrites and constituent inclusions, plot along a line with a slope close to 1 (Fig. 2). As such variation does not show any mass dependency, it is generally referred to as mass-independent fractionation. Clayton et al. (1973) initially suggested that slope 1 variation in meteorites resulted from an early injection into the Solar System of a hypothetical component composed almost exclusively of ^{16}O . Experimental work undertaken by Thiemens and Heidenreich (1983) demonstrated a possible alternative mechanism when it was found that ozone formation was associated with a slope 1 oxygen isotope anomaly.

Failure to identify the putative ^{16}O -rich component led Clayton (2002) to suggest that early Solar System mass-independent variation might have been caused by photodissociation of CO, followed by self-shielding. Clayton (2002) further proposed that the site of this process was the x-wind spot close to the young Sun (Shu et al. 2001). Other sites that have been proposed for the operation of this process are, the edge of the solar nebula (Lyons and Young 2005), or the precursor molecular cloud from which the Solar System formed (Yurimoto and Kuramoto 2004; Yurimoto et al. 2007).

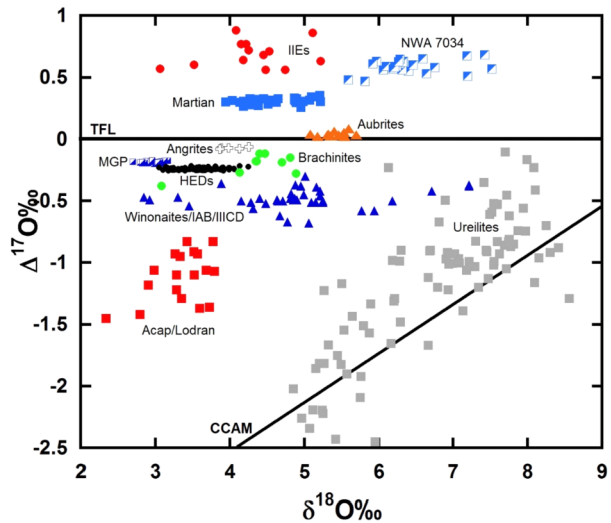
In the years since the breakthrough discovery of Clayton et al. (1973), extensive analysis of meteorites and their components has shown that they generally have distinct compositions in oxygen three-isotope space (Clayton 2003, 2006; Franchi 2008; Greenwood et al. 2017) (Fig. 3). Planets are no exception and the two such bodies from which we have samples, Mars and Earth, have distinct oxygen isotope ($\Delta^{17}\text{O}$) compositions (+0.3‰ for Mars and 0‰ for Earth). (Fig. 3). The Moon has essentially the same $\Delta^{17}\text{O}$ composition as the Earth for reasons which most likely reflect its mode of formation in a giant impact event (Wiechert et al. 2001; Spicuzza et al. 2007; Hallis et al. 2010; Young et al. 2016; Greenwood et al. 2018b). However, an alternative view for the Earth-Moon isotopic similarity is that it reflects the near-identical planetary feeding zones from which the proto-Earth and the giant impactor accreted (Dauphas et al. 2014; Dauphas 2017). As will be discussed in further detail in the following sections, what is required to solve these controversies is a sample from Venus (Stevenson and Halliday 2014).

2.5 The Bimodal Solar System

2.5.1 How are Planets Built?

At the largest scale, the Solar System has a distinct bimodal structure, comprising an inner zone of rocky terrestrial planets and an outer region of giant planets (Morbidelli et al. 2015). The processes which led to this dichotomy remain poorly understood (Chambers 2016; Walsh and Levison 2019; Weidenschilling 2019). One possibility is that the giant planets

Fig. 3 Oxygen isotope diagram of planetary and achondritic meteorites (Modified after Greenwood et al. 2017)



grew large because of the presence of additional components, such as ices and organics that were essentially not available in the inner Solar System (Chambers 2016; Morbidelli 2018; Weidenschilling 2019). But such a simple explanation does not take into account the rapid timescales involved. Protoplanetary discs typically exist for relatively short time periods of only about 6 Myr or less (Haisch et al. 2001) and without other factors being involved, accretion in the outer Solar System would have been too slow to explain the existence of giant planets (Thommes et al. 2003).

Planetary growth models start with dust grains in a gaseous disc. Interactions with the gas give the grains varying velocities that promote frequent collisions. Initially at least, grains stick together and form larger and larger aggregates (Blum 2018; Weidenschilling 2019). This process has been termed collisional coagulation (Weidenschilling 2019). However, there appears to be a size limit to this process, generally referred to as the “metre-size barrier” (Morbidelli 2018). Essentially, this is a reflection of the fact that above a certain grain-size, mutual collisions are destructive, rather than constructive. The actual limit varies according to the radial distance from the proto-Sun, being approximately mm-sized in the inner disc and cm-sized or greater in the outer disc (Morbidelli 2018). Two processes have been proposed to overcome this difficulty: i) turbulent concentration and ii) streaming instabilities (Weidenschilling 2019). The first of these mechanisms involves the formation of dense clumps of chondrule-sized particles in regions of lower vorticity within a turbulent velocity field (Cuzzi et al. 2010; Weidenschilling 2019). Such dense clumps become susceptible to gravitational collapse, leading to the formation of bodies that significantly exceed the metre-size limit (Cuzzi et al. 2010). Where a disc is non-turbulent, clumping can still take place via streaming instabilities (Youdin and Goodman 2005; Morbidelli 2018; Weidenschilling 2019). This involves zones with higher amounts of solid interacting with gas, such that the inwards drift of these denser clumps is reduced compared to isolated particles. As a consequence, isolated particles which lie outwards from such a denser zone will be spiralling in at a faster rate and so tend to merge with the denser clump. This produces a positive feedback with the clump gradually increasing its mass. This will eventually result in its contraction due to self-gravity and result in the formation of a planetesimal (Morbidelli 2018).

Following the emergence of a planetesimal population, planet formation is classically considered to proceed via a series of discrete stages. This commences with “runaway growth” in which the largest planetesimal in a local region grows at a faster rate than its smaller neighbours. Once this body attains about half the local mass it begins to perturb the orbits of its smaller neighbours. As a result, relative velocities increase, leading to a process termed “oligarchic growth” (Walsh and Levison 2019). At the end of this phase a bimodal population is formed consisting of relatively few, large planetary embryos and a much larger number of remaining planetesimals. The final step involves planet-building via energetic impacts between embryos and is termed the “giant impact” or “chaotic growth” stage (Walsh and Levison 2019).

The classic stages of planetary growth outlined above may not occur rapidly enough to account for the formation of the outer giant planets (Morbidelli 2018). Instead, once planetesimals formed, further growth may have involved a process known as pebble accretion (Lambrechts and Johansen 2012; Johansen and Lambrechts 2017). This model is based on the premise that newly-formed planetesimals were embedded within a disc of gas containing small solid particles, or “pebbles”. These particles would be strongly coupled to the gas and hence undergo drifting with respect to the planetesimals. As pebbles collide and are incorporated into the growing planetesimal the accretion zone around the body is continuously replenished by new solids and hence accretion rates are significantly greater than predicted by classical growth models. The distinction between the inner and outer Solar System may have taken hold at this stage (Morbidelli et al. 2015). Pebbles inward of the snow line may have been less massive than those outside it. The result is that sub-Moon-sized planetesimals in the inner Solar System only attained Mars-sized dimensions, whereas in the outer Solar System they reached 20 Earth masses (Morbidelli et al. 2015). Initial planetesimal size may also have been an important factor in controlling the size of bodies that eventually formed in the inner disc, with inside-out accretion being favoured by larger-sized primordial planetesimals (Walsh and Levison 2019). The growth of Jupiter may have taken place by a complex sequence, initially involving a rapid phase of pebble-accretion, then a slower stage of planetesimal accretion, with a final stage of runaway gas accretion (Alibert et al. 2018).

2.5.2 Isotopic Evidence for a Bimodal Solar System

The Solar System is not only bimodal in terms of its overall structure but also shows a clear dichotomy at the level of its bulk and isotopic composition. Based on data from a number of earlier studies (e.g. Trinquier et al. 2007; Qin et al. 2010), Warren (2011) showed that Solar System materials have a bimodal composition with respect to a number of isotopic systems ($\Delta^{17}\text{O}$, $\varepsilon^{54}\text{Cr}$, $\varepsilon^{50}\text{Ti}$, $\varepsilon^{62}\text{Ni}$). Thus, on a plot of $\varepsilon^{54}\text{Cr}$ vs. $\Delta^{17}\text{O}$ two groups are present (Fig. 4). One comprises the carbonaceous chondrites and a minor subset of achondrites. The other group is defined by all other Solar System materials, including planetary-derived samples (Mars, Earth, and Moon), ordinary and enstatite chondrites and a wide range of achondrites (main-group pallasites, HEDs, ureilites, aubrites). Warren (2011) suggested that the carbonaceous chondrite group (CC) may comprise material formed in the outer Solar System and the non-carbonaceous chondrite group (NC) in the inner Solar System. The gap between the NC and CC groups has been referred to as “The Warren Gap” (e.g. Voosen 2018). It has now been demonstrated that the isotopes of a wide group of elements display the dichotomy seen in Fig. 4 (Warren 2011; Budde et al. 2016; Van Kooten et al. 2016; Kruijjer et al. 2017, 2020; Burkhardt et al. 2019). Iron meteorites also display a similar bimodal distribution of nucleosynthetic anomalies (e.g. Budde et al. 2016).

With the notable exception of oxygen, isotopic mass-independent variation in Solar System materials, which is not caused by either spallation or radioactive decay, is the result

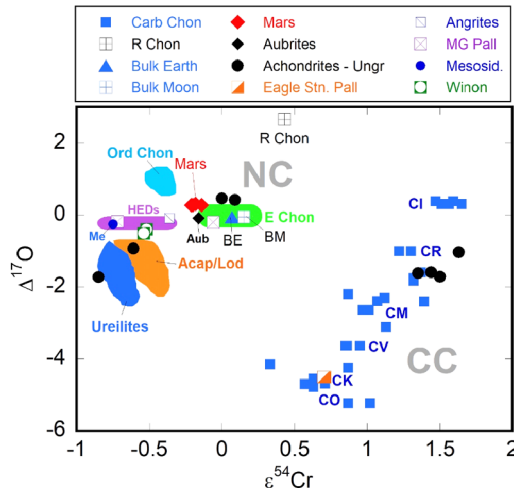


Fig. 4 Plot of $\epsilon^{54}\text{Cr}$ vs. $\Delta^{17}\text{O}$ for a range of planetary materials. Carbonaceous chondrite (CC) and non-carbonaceous (NC) groups show a clear separation. The NC group includes the ordinary chondrites (Ord Chon), enstatite chondrites (E Chon), R chondrites (R Chon), Bulk Earth (BE), Bulk Moon (BM), martian meteorites (Mars), ureilites, mesosiderites (ME), acapulcoite – lodranite suite (Acap/Lod), aubrites (Aub), howarite-eucrite-diogenite suite (HEDs). The CC group includes all the carbonaceous chondrites as well as the Eagle Station pallasites and various ungrouped achondrites (Modified after Warren 2011; Greenwood et al. 2017, 2020)

of nucleosynthetic processes that took place in the precursor stars from which the Solar System formed (Dauphas and Schauble 2016; Scott et al. 2018 Burkhardt et al. 2019; Nanne et al. 2019). The isotopic variation observed in Solar System materials likely reflects the heterogeneous distribution of the presolar carrier grains (Kruijjer et al. 2020) and suggests that the mixing and homogenisation processes that took place in the precursor molecular cloud and later in the protoplanetary disc, were not sufficient to erase these anomalies (Burkhardt et al. 2019; Nanne et al. 2019; Kruijjer et al. 2020).

In contrast, oxygen mass-independent isotopic variation likely had a non-nucleosynthetic origin (Clayton 2002). The most widely accepted formation model involves selective UV photo-dissociation of CO, either in the presolar giant molecular cloud, or in the solar nebula itself (Clayton 2002; Yurimoto and Kuramoto 2004; Lyons and Young 2005). The oxygen isotope anomalies produced by this process would have become incorporated into different phases, including water ice, gas and dust (Yurimoto and Kuramoto 2004). Preservation of such isotopic differences may again be a reflection of incomplete homogenization in the protosolar nebula (Ireland et al. 2020).

Evidence from the Stardust sample return mission (Brownlee 2014) suggests that large-scale mixing of gas and dust was taking place during the earliest stages of Solar System evolution. In view of this, an important and not yet fully resolved question is why the NC-CC dichotomy was not erased at an early stage due to vigorous mixing. In terms of how the anomaly was initially established, recent studies have suggested that it may reflect a change in the composition of the fresh infalling material that was feeding the proto-solar nebula (Burkhardt et al. 2019; Nanne et al. 2019; Kruijjer et al. 2020). Calcium Aluminium-rich inclusions (CAIs) are generally considered to have formed at an early stage in nebular evolution and at a location that was close to the proto-Sun (Shu et al. 2001; Ireland et al. 2020). CAIs thus preserve a record of the isotopic composition of the earliest infall to the

proto-solar disc. The evidence from CAIs is that this early material was enriched in nuclides produced in neutron-rich stellar environments. This infall material, including CAIs, would have been transported outwards through viscous spreading (Kruijer et al. 2020). Following this early stage of disc accretion, it is suggested that there was a change in the composition of the infalling solids, which became depleted in neutron-rich nuclides. These later solids would have tended to accumulate in the inner part of the disk and have diluted the isotopic signature originally present there (Kruijer et al. 2020). Thermal processing of solids in the hotter inner part of the disc (Scott et al. 2018), may not have been a major contributory process in the establishment of the NC-CC dichotomy (Nanne et al. 2019). One explanation that has been advanced to explain the preservation of the NC-CC dichotomy is that it can be related to the early, rapid accretion of Jupiter, which during the later stages of its growth would have formed a barrier separating the inner and outer Solar System regions (Kruijer et al. 2017, 2020).

The role of Jupiter in preserving the NC-CC dichotomy has been disputed by Brasser and Mojzsis (2020). They suggest that Jupiter's accretion took place at too slow a rate to have been a significant barrier to lateral mixing within the disc. Brasser and Mojzsis (2020) instead invoke a pressure maximum in the disc close to the present location of Jupiter and suggest that it was this feature, rather than the planet itself, which prevented mixing between the inner and outer disc. In a companion paper (Burbine and Greenwood 2020), a sample return mission to Ceres is proposed as a means of investigating in detail the origin and early evolution of the CC group.

Bimodality is also evident in the bulk composition of extraterrestrial samples. There is a well-established dichotomy between carbonaceous chondrites on the one hand and ordinary and enstatite chondrites on the other (Weisberg et al. 2006; Krot et al. 2014). Carbonaceous chondrites generally contain abundant CAIs, predominantly plot below the terrestrial fractionation line (TFL) on an oxygen three-isotope diagram and show evidence of having accreted water ice into their parent bodies (e.g. Grimm and McSween 1989; Trigo-Rodríguez et al. 2019). In contrast, ordinary and enstatite chondrites generally show anhydrous characteristics, plot on or above the TFL and have a relatively low CAI content (Weisberg et al. 2006; Krot et al. 2014).

2.6 Is the Inner Solar System Heterogeneous or Homogeneous? Sorting Out the Giant Impact Once and for All?

The question as to whether the inner Solar System is isotopically heterogeneous or homogeneous would appear at first glance to be fairly straightforward. Based on the evidence of Fig. 4 and similar plots of $\epsilon^{50}\text{Ti}$ vs. $\epsilon^{54}\text{Cr}$ (Warren 2011; Scott et al. 2018) it would seem that the inner Solar System (NC) group, while distinct from the carbonaceous chondrite (CC) group, still displays a significant level of heterogeneity. If such lithologies are representative of the material that formed in the inner Solar System then mixing and homogenisation was far from complete. However, there are problems with this analysis. Apart from the Earth, Moon and Mars, the other non-carbonaceous chondrite lithologies plotted in Fig. 4 are all asteroidal in origin and hence derived from very small bodies. In fact, all of the mass in the asteroid belt is estimated to represent just 0.04% that of the Earth (Pitjeva and Pitjev 2018) (see also Table 1) and so can hardly be considered to be representative. Although much more massive than the asteroid belt, Mars is anomalously small compared to either Earth or Venus (Table 1). One of the drivers for the formulation of the Grand Tack model was to explain the relatively small size of Mars (Walsh et al. 2011, 2012). As a result of the inward and then outward migration of Jupiter, the Grand Tack model predicts that the feeding zone for Mars

was significantly impoverished, hence its small size. This suggests that Mars is also not fully representative of the inner Solar System, which leaves just Earth and the Moon in terms of relatively large bodies from the inner zone of the Solar System from which we already have samples.

While both the Earth and Moon are almost identical in terms of their $\Delta^{17}\text{O}$ compositions, as discussed above, this may be the result of very high energy mixing in the wake of a giant impact (Wiechert et al. 2001; Spicuzza et al. 2007; Hallis et al. 2010; Young et al. 2016; Greenwood et al. 2018b). However, an alternative hypothesis, which helps to maintain the basic tenants of the canonical giant impact model (low-energy, oblique impact) (Canup and Asphaug 2001), postulates an impactor, which was essentially isotopically identical to the proto-Earth (Dauphas et al. 2014; Dauphas 2017). Evidence from multiple isotopic systems suggests that during a significant portion of its accretion Earth was fed by compositionally homogeneous enstatite chondrite-like material (Dauphas 2017). This implies that the inner Solar System may have been well-mixed prior to the Giant Impact. To test such a hypothesis we need a sample from another large inner Solar System body, either Venus or Mercury. While it would be optimal to have samples from both planets and this should be a long term strategic, exploration goal, a choice would need to be made in the short term. Mercury appears to have an anomalously high iron content that may reflect a complex history of multiple giant impacts with loss of crustal and mantle material (Chau et al. 2018). It is also much smaller than Venus (Table 1). Hence, Venus must be regarded as a more representative inner Solar System sample return target.

Aubrites are the achondrites with the closest oxygen isotope composition to Earth with respect to $\Delta^{17}\text{O}$ (Greenwood et al. 2018b). Using aubrites as a proxy for the giant impactor, Greenwood et al. (2018b) were able to demonstrate that, at high precision, a clear oxygen isotopic difference between the Earth and Moon should be observed if the impact conditions were those defined by the canonical model (Canup and Asphaug 2001). The magnitude of this difference would far exceed the maximum 4 ppm isotopic difference actually measured in lunar and terrestrial samples by Greenwood et al. (2018b). It was concluded by Greenwood et al. (2018b) that the giant impact was significantly more energetic than the canonical model suggests and most likely resembled the situation envisaged by the “Synestia” simulations of Lock et al. (2016) and Lock and Stewart (2017). However, analysis of another large inner Solar System body is needed to test this further. As pointed out by Stevenson and Halliday (2014), we don’t know whether “the Earth and Moon are unusual in being so similar isotopically”. It is also possible that the inner Solar System experienced a very advanced level of homogenisation and that the giant impactor which formed our Moon was an example of such a body. If the impactor was more Earth-like than aubrites in terms of its isotopic composition then the canonical giant impact model may represent a more realistic scenario than is currently believed. A sample from Venus would undoubtedly help to resolve this controversy.

2.7 What was the $\Delta^{17}\text{O}$ Structure of the Inner Solar System?

With the notable exception of meteorites from Mars, the Moon and Vesta, it is generally very difficult to link asteroids and meteorites (Greenwood et al. 2020). A further complication is the prediction of the Grand Tack model that the material present in the asteroid belt is not indigenous to this region, but instead may have formed at varying locations throughout the early Solar System (Walsh et al. 2011, 2012). However, as pointed out by Goodrich and O’Brien (2014) in the case of the ureilite parent body, knowing the heliocentric distance at which an asteroid accreted is a critical piece of information in trying to understand early

Solar System evolution. A concept that is frequently discussed in meteorite studies is the proposition that the $\Delta^{17}\text{O}$ of parent bodies varies sequentially with heliocentric distance (e.g. Rubin and Wasson 1995; Kallemeyn et al. 1996). In its broadest sense this concept suggests that parent bodies with $\Delta^{17}\text{O}$ values close to or above the TFL e.g. Mars, Earth, ordinary and enstatite chondrites, R chondrites, may have formed closer to the Sun than those with negative $\Delta^{17}\text{O}$ values, such as the carbonaceous chondrites. While in an overall sense this concept may have value and appears to be a forerunner of the bimodal view of the Solar System discussed in Sect. 2.5, in detail the oxygen isotopic evolution of the solar nebula was complex (Yurimoto et al. 2007; Lyons et al. 2009) and a simple and systematic variation in $\Delta^{17}\text{O}$ with heliocentric distance is likely to be an over simplification. However, without a sample from another large inner Solar System body we have no way of testing whether there is any relationship between $\Delta^{17}\text{O}$ and heliocentric distance.

The later stages of terrestrial planet formation are thought to involve the accretion of several hundred Moon-sized bodies (Kaib and Cowan 2015). The final $\Delta^{17}\text{O}$ value of a planet is therefore likely to be the weighted average of the $\Delta^{17}\text{O}$ values of these contributing bodies (Young et al. 2016). In theory then, the values for the Earth and Venus could be significantly different, just as they are for Earth and Mars (Fig. 3). On the other hand, if the inner Solar System underwent an early stage of homogenisation and Mars is an outlier, as predicted by the Grand Tack model (Walsh et al. 2011, 2012), then Earth and Venus could have nearly identical $\Delta^{17}\text{O}$ values. It is impossible to discriminate between these two possibilities without a sample from Venus. In conclusion, the $\Delta^{17}\text{O}$ value for Venus would likely have profound implications both for the formation of our own Solar System and by extrapolation for other exoplanetary systems (e.g. Torres and Fressin 2019).

3 Venus: A Brief Geological Overview

In this section we provide a brief overview of venusian geology, focussing in particular on the structure and composition of its surface. The aim of this section is to suggest potential terrains which could be sampled by a robotic mission to Venus.

3.1 Planetary Parameters

Venus is Earth's closest planetary neighbour and the two bodies show a number of striking similarities in terms of their overall size and structure. Venus is slightly smaller than Earth having a relative mass, volume and mean radius compared to our planet of 81.5%, 85.7% and 95%, respectively (Williams 2018a). The uncompressed density of Venus is nearly identical to that of Earth and hence both planets are considered to have similar internal structures and compositions (Taylor et al. 2018). Venus is situated 0.72 AU from the Sun and in theory resides within the Solar System's habitable zone (Byrne et al. 2019). Based on the results of modelling studies, Venus is thought to have a large metallic core, broadly similar to that of Earth (Zhang and Zhang 1995). However, unlike Earth, Venus does not have a significant global magnetic field (Jacobson et al. 2017). The reason for this is poorly understood. Venus has a 243 day retrograde rotation, the slowest for any planet. However, in theory this would still be sufficient to generate an Earth-like magnetic field (Stevenson 2003; O'Rourke et al. 2018). One possible reason for the lack of a core dynamo is that "normal" planetary accretion processes result in a compositionally stratified core which is gravitationally stable and hence does not undergo convection, which may be the case for Venus (Jacobson et al. 2017). In contrast, Earth experienced a late-stage, Moon-forming, giant impact

that may have homogenized its core, resulting in the onset of thermal convection (Jacobson et al. 2017). The possible lack of a late stage giant impact is only one of a range of scenarios that might explain the absence of a core dynamo on Venus (Smrekar et al. 2018). It is also possible that the core of Venus may already have totally crystallised or that the magnetic dynamo may be episodic in nature (Smrekar et al. 2018).

Although the present day venusian atmosphere is essentially dry, the primordial water content of the planet was probably similar to that of Earth (Taylor et al. 2018). The D/H ratio of water in the venusian atmosphere is between 95 and 120 times greater than that on Earth (Krasnopolsky et al. 2013), consistent with models that Venus started with a water inventory similar to Earth's and that this was then lost over time to space (Donahue et al. 1982; Greenwood et al. 2018a). Hydrogen and oxygen can rapidly escape from a planetary atmosphere following photolysis of water under conditions of strong X-ray and ultraviolet radiation (Guo 2019). Kasting and Pollack (1983) indicate a timescale of about a billion years for Venus to have lost one terrestrial ocean equivalent of water by hydrodynamic escape, whereas Guo (2019) suggests an early and much more rapid process of atmospheric desiccation.

Tectonic processes on Venus are considered to be very different to those operating on Earth (Turcotte 1993; Ghail 2015). A random distribution of craters across the surface of the planet is taken as evidence that the crust of Venus acts like a single rigid plate that is gradually thickening due to conductive cooling (Turcotte 1993). This tectonic regime is generally referred to as a "stagnant lid" (Ghail 2015) and may be a consequence of the high viscosity of the venusian mantle, due to low concentrations of water (Nimmo and McKenzie 1998). In contrast to Earth, Venus appears to experience global resurfacing events, the last being 300 to 600 Myr ago (Nimmo and McKenzie 1998). The heat flux on Venus is currently about half that expected from radiogenic heat production, suggesting that Venus is currently heating up internally (Nimmo and McKenzie 1998).

3.2 Surface Geology

The following account of the surface geology of Venus is derived mainly from Basilevsky and McGill (2007); Ivanov and Head (2011) and Taylor et al. (2018). The venusian surface is dominated by volcanic plains (~80% of total area), which show varying degrees of deformation. The plains have been divided into a number of distinct terrains, which include: (i) densely fractured plains, (ii) ridge belts, (iii) regional plains, (iv) shield plains, (v) lobate plains and flows, (vi) smooth plains (Basilevsky and McGill 2007; Ivanov and Head 2011).

Densely fractured plains occupy 3 to 5% of the planetary surface and form small isolated areas up to 200 km in diameter, elevated a few hundred metres above the regional plains. As their name suggests, densely fractured terrains are composed of intensely fractured material. Ridge belts are slightly elevated above the regional plains and comprise material that has been deformed into elongate ridges that tend to run subparallel to the belt margins (Fig. 6). Ridge belts comprise 3 to 5% of the venusian surface. Regional plains tend to have smooth surfaces with flow-like structures suggesting that they may represent basaltic lavas of low viscosity (Basilevsky and McGill 2007) (Fig. 7). A characteristic feature of the regional plains is the development of narrow, but hundreds of kilometre long, "wrinkle ridges" (Fig. 7). Regional plains occupy 50 to 60% of the planetary surface. Shield plains are areas that consist of coalescing larger volcanic shield volcanoes, each a few hundred kilometres across, which in turn are covered by smaller, 5 to 15 km diameter shield volcanoes. Shield plains comprise 10 to 15% of the surface of Venus. Lobate plains and flows generally

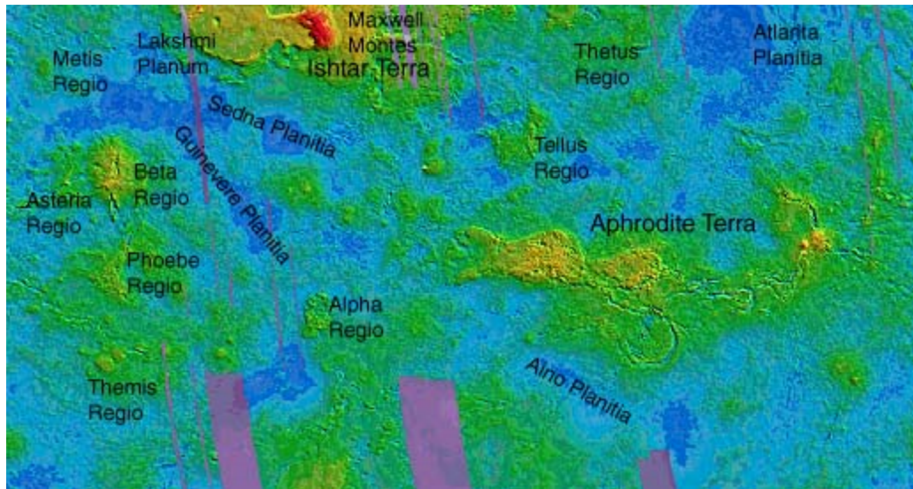


Fig. 5 Altimeter topographic map of Venus constructed using data from the Magellan orbiter. Map is displayed in Mercator projection. Unmapped areas shown in grey. Red areas highest and blue lowest. Synthetic shading added to enhance visibility of features. Credit NASS/JSC

have a distinct cusped morphology and are sometimes associated with volcanic structures. Lobate plains and flows comprise about 10% of the planet's surface and show variable radar brightness, suggesting different surface textures. Smooth plains appear dark in radar images and occupy only a few percent of the venusian surface.

Distinct from the plains are elevated areas, known as tessera terrains which occupy about 8% of the surface of Venus (Basilevsky and McGill 2007; Ivanov and Head 2011). The two largest "highland" areas dominated by tessera terrains are Ishtar Terra in the north and the somewhat larger, more southerly, Aphrodite Terra (Fig. 5). Tessera terrains are the most highly deformed regions on Venus and are characterised by numerous intersecting ridges and grooves, which are typically a few kilometres wide and tens of kilometres long (Basilevsky and McGill 2007; Whitten and Campbell 2019). Ridge features are considered to have formed by compressional tectonics and the grooves by extension. Tessera terrains appear to represent the oldest units on Venus and tend to appear bright on Magellan radar images (Fig. 8). The composition of the material forming the tessera terrains is unknown, with alternative suggestions that they may be either basaltic or feldspathic (anorthosite/granite) in nature (Basilevsky and McGill 2007; Gilmore et al. 2017). Tessera terrains are often associated with mountain belts, as is clearly seen in the case of Ishtar Terra, which contains the highest mountain on Venus, Maxwell Montes (Fig. 5). The mountain belts are considered to have been formed by compressional tectonics and may be of similar age to the tessera terrains (Basilevsky and McGill 2007). The absolute age of either the mountain belts or tessera terrains is unknown.

Some of the landforms found on Venus are generally considered to be unique to the planet. These include flat-topped volcanic features known as "pancake-domes" or "lava domes" or "farra" (Fig. 9). These can be up to 70 km diameter and rise up to 1 km above the surrounding plains. There are also star-like features termed "novae" (Fig. 10) and structures which comprise both radial and concentric fractures, termed "arachnoids" based on their resemblance to spider's webs (Fig. 11). Circular rings sometimes surrounded by a depression are termed "coronae" (Fig. 12). All of these landforms are likely to be volcanic in origin.



Fig. 6 Magellan full resolution radar mosaic of the Lavinia region of Venus. The mosaic is centred at 50 degrees south latitude, 345 degrees east longitude, and spans 540 km north to south and 900 km east to west. A diverse set of geologic features are shown on the image. The bright area running from the upper right to the lower left is interpreted as part of a belt of ridges, formed by compression and thickening of the upper layers of the planet. The areas between ridges suggest flooding by smoother lavas. The varied texture of the lavas can be seen in the mottled appearance of the plains, which are cut by the ridges. Brighter, rougher flows are also common. The particularly bright flows in the lower right corner are the northern extension of Mylitta Fluctus. The bright ridges adjacent to Mylitta Fluctus at the bottom centre of the image also appear to have been affected by the volcanic activity. Some of these bright features have been interpreted as down-dropped areas roughly 5 km wide. This would imply a region of extension where the crust has been pulled apart and so was more easily flooded by the later lava flows. The thinner fractures running from the upper left seem to end at the ridge belt in the centre of the mosaic. These thinner fractures are a continuation of a pattern seen throughout much of Lavinia and suggest a pattern of compression over a very large region. (Image credit: NASA/JSC. Caption modified from original JSC version)

The dense cloud cover on Venus means that surface temperatures show only slight variations and as a result surface winds are slow and not effective agents of erosion. This coupled with the lack of water, may explain why there is such a diversity of surface features on Venus (Basilevsky and McGill 2007).

Volcanism appears to be the dominant process shaping the surface of Venus (Taylor et al. 2018). There is evidence that Venus remains volcanically active. The Venus Express orbiter detected transient high emissivity anomalies associated with the Ganiki Chasma rift zone in the northern Atla Regio region, which are thought to represent recent eruptions of surface lava (Shalygin et al. 2015; Gilmore et al. 2017).

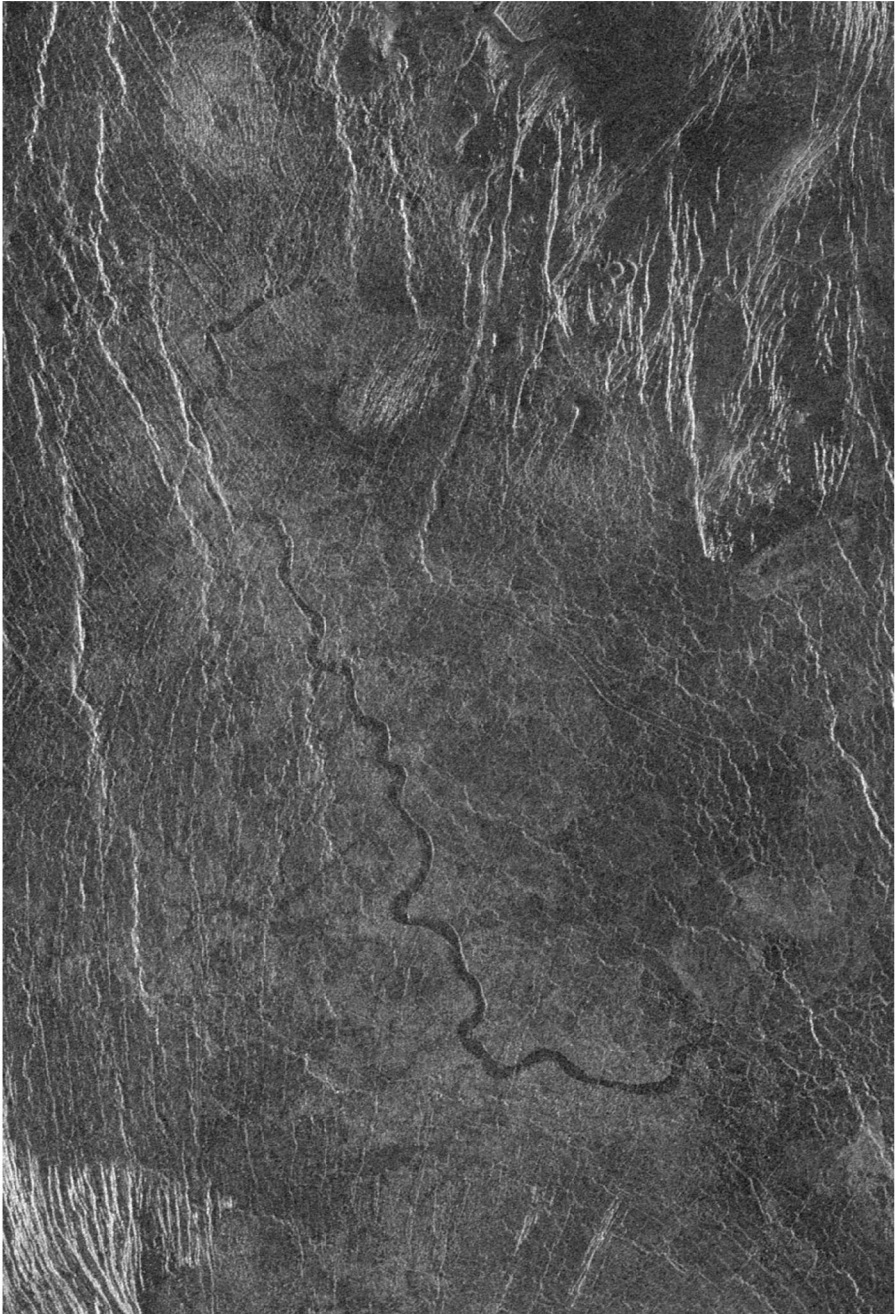


Fig. 7 Full resolution radar mosaic from Magellan at 49 degrees south latitude, 273 degrees east longitude. The area shown has dimensions of 130 by 190 km. The sinuous channel at the centre of the image is approximately 200 km long by 2 km wide. Similar channel-like features are common on the plains of Venus. In some places they appear to have been formed by lava which may have melted or thermally eroded a path over the plains' surface. Most channels are partly buried by younger lava plains, making their sources difficult to identify. (Image credit: NASA/JSC. Caption modified from original JSC version)

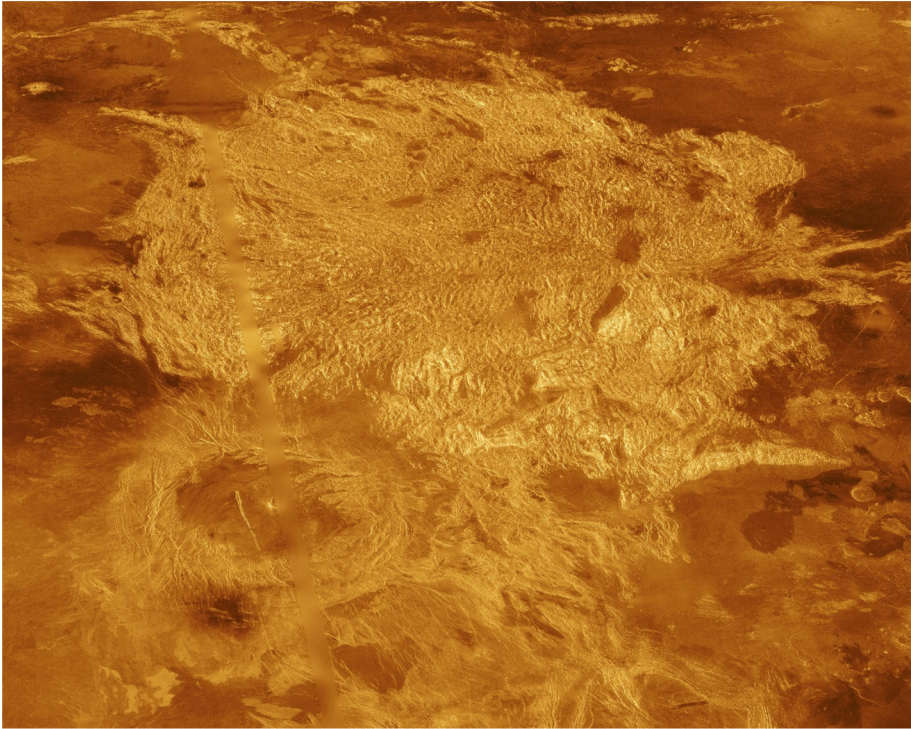


Fig. 8 A three-dimensional perspective view of the Alpha Regio region, which is a topographic upland approximately 1300 km across, centred on 25 degrees south latitude, 4 degrees east longitude. The radar-bright area of Alpha Regio is characterized by multiple sets of intersecting structural features, such as ridges, troughs, and flat-floored fault valleys that together form a polygonal outline. Directly south of the complex ridged terrain is a large ovoid-shaped feature named Eve. (Image credit: NASA/JPL Caption modified from original JSC version <http://photojournal.jpl.nasa.gov/catalog/PIA00481>)

Almost 1000 impact craters are evenly spread across the surface of Venus. Most are in almost pristine condition and this has led to the proposition that Venus underwent a global resurfacing event 300 to 600 Myr ago. This is thought to reflect the lack of plate tectonics on Venus (Turcotte 1993; Ghail 2015). In contrast to the continuous subduction of crustal material that occurs at destructive plate boundaries on Earth, Venus experiences a cyclic process whereby its mantle gradually heats up until the crust is weakened and subduction then takes place on an enormous scale. No crater on Venus is less than 3 km diameter. This probably reflects filtering by the thick atmosphere which slows down any incoming bolides that are less than about 50 m in diameter.

3.3 What Samples to Collect and Where?

It is clear from the previous sections that the surface of Venus displays great structural diversity and to an unknown extent may also be compositionally diverse. However, the surface geology does appear to be dominated by the products of basaltic volcanism, with the possible exception of the tessera terrains (Basilevsky and McGill 2007). An important first order issue for any sample return mission would be to decide what sort of terrain should be targeted to gain the maximum amount of information about the planet. The various plains units

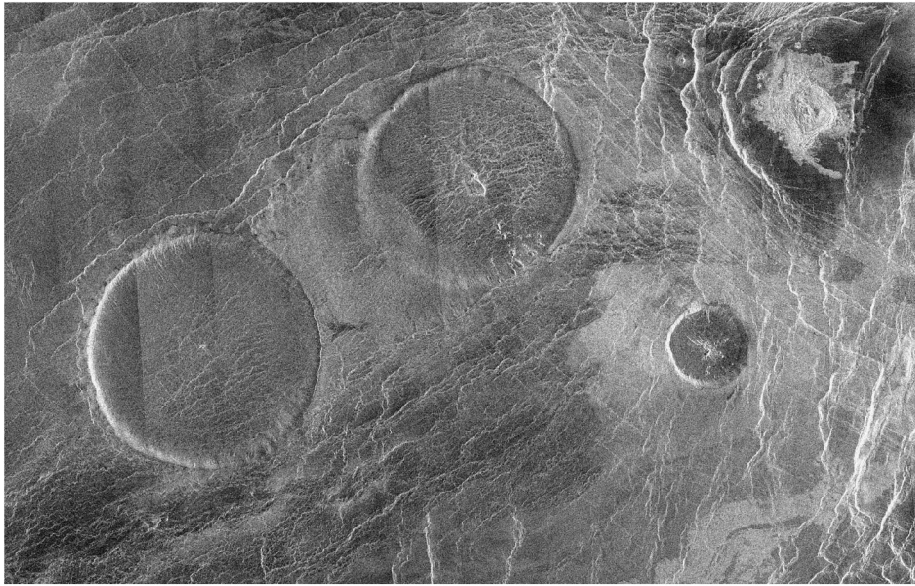


Fig. 9 Magellan full resolution mosaic, centred at 12.3 north latitude, 8.3 degrees east longitude, showing an area 160 km by 250 km in the Eistla region of Venus. The prominent circular features are volcanic domes, 65 km in diameter with broad, flat tops less than one km in height. Sometimes referred to as ‘pancake’ domes, they represent a unique category of volcanic edifice on Venus formed by the extrusion of viscous lava. The cracks and pits commonly found in these features may result from cooling and withdrawal of lava. (Image credit: NASA/JPL. Caption modified from original JSC version)

comprise 80% of the planet’s surface, so that a sample collected from these areas would clearly be the most representative. On the other hand, there is some evidence to suggest that the tessera terrains are both older and compositionally distinct from the other units on Venus (Gilmore et al. 2019). A single sample from such a terrain might prove to be a Rosetta stone, capable of yielding an enormous amount of information about the evolution of Venus. But from one perspective it doesn’t really matter where the returned venusian samples are collected. As discussed earlier, the most important single piece of information we seek to acquire from returned samples is their $\Delta^{17}\text{O}$ composition and this should be the same no matter what terrain they are collected from.

In their study of potential landing sites on Venus, Basilevsky et al. (2007) recommended that for lander missions undertaking “in situ” analysis, “true” tessera terrains would be of highest importance, with other terrains of secondary importance. Interestingly, they switched this priority for sample return missions and suggested that the highest priority target were the regional plains with wrinkle ridges, with the tessera terrains only of secondary importance. Basilevsky et al. (2007) consider that as the regional plains are the most widespread unit on Venus, full geochemical and isotopic analysis of this material back on Earth would provide the maximum amount of information about the processes operating in the mantle and crust of the planet.

The extent to which individual terrains have experienced surface weathering is a further important constraint on landing site selection. As pointed out by Taylor et al. (2018), the high pressures and temperatures that prevail at the surface of Venus and the reactive species present in its atmosphere, such as SO_2 , HCl and HF , are likely to result in significant levels of surface-atmosphere interaction. This problem may be compounded

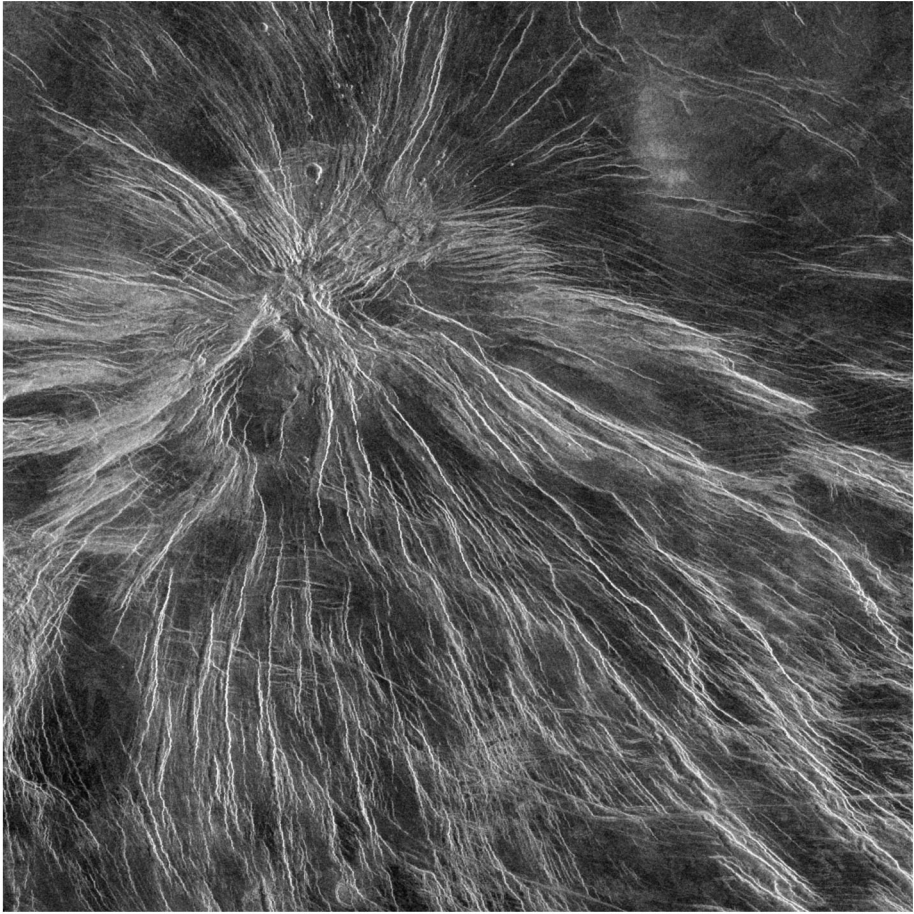


Fig. 10 Magellan image of a nova, a radial network of grabens, in Themis Regio, Venus. There have been about 50 novae identified on Venus, which consist of closely spaced graben radiating from a central area. This nova is about 250 km in diameter. (Image credit: NASA/JPL. Caption modified from original JSC version)

by the fact that the atmosphere and lithosphere on Venus are unlikely to be in isotopic equilibrium, as is also the case for Earth and Mars (e.g. Thiemens et al. 1995; Farquhar et al. 1998). It is therefore possible that surface samples may have been isotopically modified as a result of extensive exchange with the atmosphere. Three strategies could be adopted to mitigate this problem. Firstly, the landing site would need to be in an area covered in relatively young, and as a consequence, fresh basaltic lavas. The volcanically active Ganiki Chasma region might be one possibility. Secondly, a drill sample of reasonable depth needs to be collected (Figs. 13, 14). Finally, a surface atmospheric sample should be returned in order to define the oxygen isotopic composition of the lower atmosphere. However, while it is certainly important to pay due attention to the issue of surface-atmosphere interactions, it should also be noted that the images returned by the Venera spacecraft suggest that appropriate sample site selection would significantly alleviate this potential problem (Fig. 13).

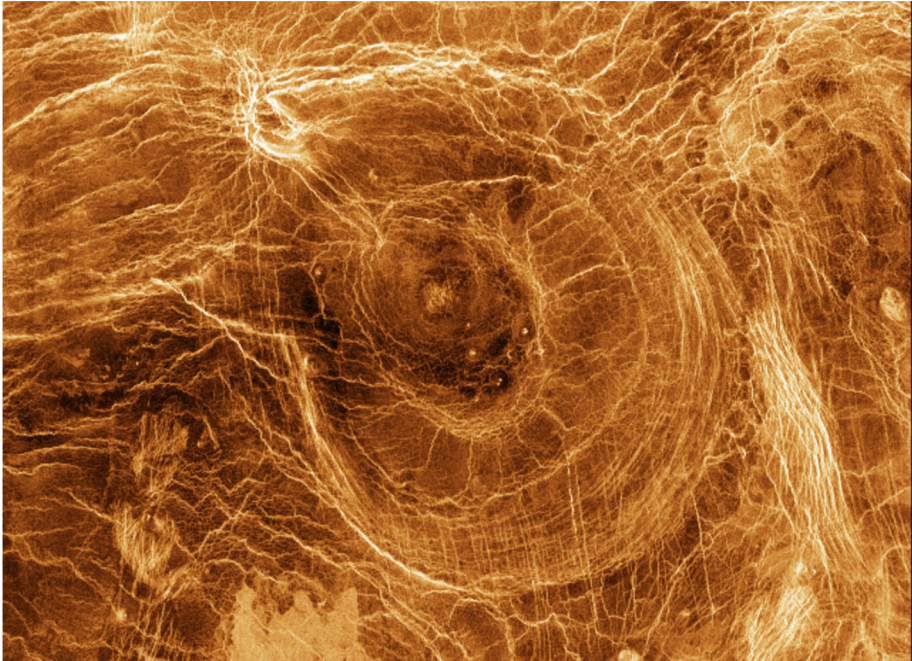


Fig. 11 Arachnoids are large structures of unknown origin that have been found only on the surface of Venus. Arachnoids get their name from their resemblance to spider-webs. They appear as concentric ovals surrounded by a complex network of fractures and can have diameters of up to 200 km. Over 30 arachnoids have been identified on Venus. (Image credit: NASA/JPL. Caption modified from original JSC version)

4 A Robotic Sample Return Mission to Venus

4.1 Studying the Surface and Atmosphere of Venus – Past Missions and Mission Proposals

Past missions to study the atmosphere and surface of Venus have been summarised by Basilevsky et al. (2007) and Taylor et al. (2018). The NASA flyby mission Mariner 2 was the first spacecraft to study Venus, arriving in December 1962. Between 1967 and 1983 a series of thirteen successful Venera missions (Venera 4 to 16) were launched by the Soviets to variously study the atmosphere and surface of Venus (Fig. 13) (Basilevsky et al. 2007). The NASA Pioneer Venus Project consisted of two spacecraft launched in 1978. One of these spacecraft was an orbiter and the other deployed four small descent probes into the venusian atmosphere, one of which reached the surface and continued to operate for over an hour. Vega 1 and Vega 2 were Soviet missions designed to study Venus and then Halley's Comet (Dolgoplov et al. 2012). Both spacecraft combined lander and balloon modules, which were inserted into the venusian atmosphere in June 1985. The Vega 1 lander experienced a large atmospheric shock during descent and so failed to operate successfully on the surface. In contrast, Vega 2 undertook surface observations for approximately an hour and successfully analysed sample material. The balloon systems deployed by Vega 1 and 2 both transmitted atmospheric data successfully for about 46 hours; a duration defined by their battery lifetimes (Sagdeev et al. 1986). ESA's Venus Express orbiter operated between 2006

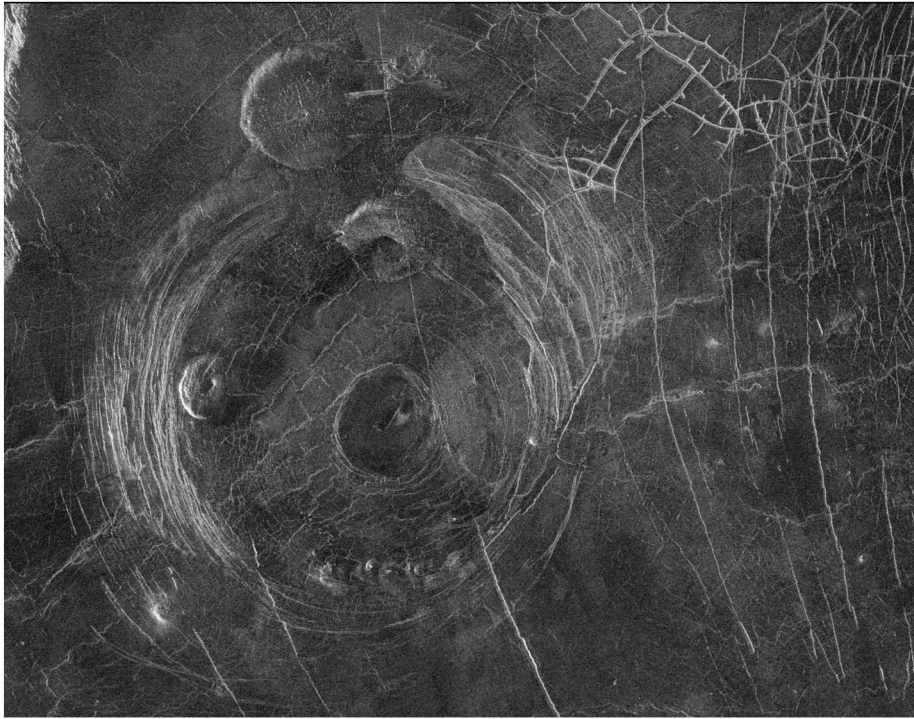


Fig. 12 Magellan radar image showing a region approximately 300 km across, centred on 59 degrees south latitude, 164 degrees east longitude and located in a vast plain to the south of Aphrodite Terra. The large circular structure near the centre of the image is a corona, approximately 200 km in diameter and provisionally named Aine Corona. Just north of Aine Corona is a 'pancake' dome about 35 km in diameter. Another pancake dome is located inside the western parts of the annulus of the corona fractures. Complex fracture patterns like the one in the upper right of the image are often observed in association with coronae and various volcanic features. (Image credit: NASA/JPL Caption modified from original JSC version)



Fig. 13 Surface image of Venus taken by the Soviet Venera 9 lander in October 1975. The angular boulders suggest only a limited degree of interaction with the venusian atmosphere. It seems likely that fresh material could be obtained by limited drilling of one of the larger, angular boulders. (Image source: Wikipedia/Ted Stryk/Planetary.org)

and 2014 and undertook detailed observations of the venusian atmosphere (Taylor et al. 2018). The JAXA Akatsuki orbiter is the only spacecraft currently studying Venus (Nakamura et al. 2016). Launched in 2010, it initially failed to enter orbit around Venus, but was later recovered and began observations of the atmosphere in 2015 (Nakamura 2019).

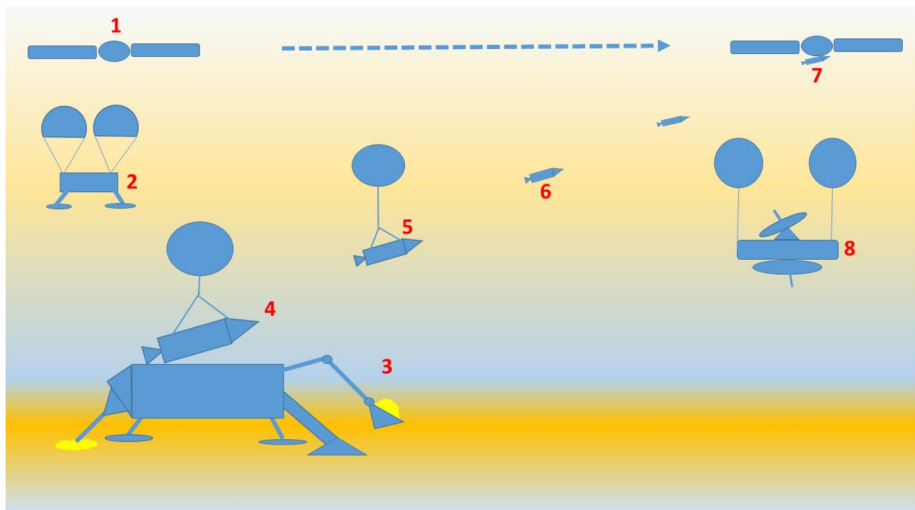


Fig. 14 Schematic diagram showing the possible stages of a “Grab and Go” sample recovery mission from the surface of Venus. This scenario is based on the detailed proposals of Rodgers et al. (2000). The original spacecraft would consist of an orbiter and a lander module. The orbiter (1) passes over the landing site every 93 mins. Once the lander has detached from the orbiter (2) it descends to the surface slowed by parachutes and possibly also rocket motors. On the surface sampling operations take place (3). The lander makes use of multiple sampling devices, including a scoop, drill and “vacuum cleaner”. Sample material is transferred to the ascent stage (4) which consists of a three part rocket (individual stages not shown). The ascent rocket is lifted to a height of 66 km by a helium balloon (5). The balloon is jettisoned and the ascent rocket (6) takes the sample back to the orbiter (7). In an extended mission scenario, a cloud-level balloon platform (8) (Chassefière et al. 2009; Wilson et al. 2019) could also be deployed, which would carry a suite of instruments to undertake detailed analysis of the venusian atmosphere. Data from the cloud-level balloon platform would be transmitted to the orbiter

A wide range of mission proposals and feasibility studies have been undertaken that involve at least some form of direct compositional analysis of venusian samples, either gaseous or solid. Most commonly, such analyses are to be carried out remotely, with a more limited number of studies proposing a return of material to Earth. Here we briefly review various proposals that involve sample return.

A detailed assessment study of how sample return from the surface of Venus could be achieved was undertaken by ESA as an in-house activity within the Directorate of Scientific Programmes (Coradini et al. 1998; Taylor et al. 1999). The mission plan envisaged two spacecraft, the first to be launched being a combined orbiter and Earth return capsule. The second spacecraft comprised a combined lander and ascent module (Whitcomb et al. 2002). Planned surface operations included collection of 100 g of rock by drilling, 100 g of dust using a “vacuum cleaner” device and 100 g of surface atmosphere. Either during the descent or ascent phases, additional atmospheric sampling was planned, involving collection of 250 ml of gas at altitudes of 15 km, 40 km and 65 km (Coradini et al. 1998). A feasibility study for a “Grab and Go” style sample return mission from the surface of Venus has also been undertaken by Rodgers et al. (2000) and is discussed in detail in Sect. 4.4. Multiple configurations to undertake both atmospheric and surface sample return have been outlined by Shibata et al. (2017).

Venera-D is a proposed Russian mission to Venus, which would comprise an orbiter and lander (Gregg et al. 2019). While the main lander is expected to only survive for two to three hours on the surface it would incorporate a longer-duration module that would operate

for between two to three months (Gregg et al. 2019). A comprehensive concept mission involving both atmospheric and surface sampling has recently been proposed by Valentian et al. (2019) in response to the ESA Voyage 2050 white paper call. The proposed mission would involve either two or three separate launches carrying a variety of probes, including two orbiters, one of which brings back the samples to Earth, a balloon sampling platform and multiple landers for surface sample collection.

4.2 How Much Sample Material Needs to be Collected?

Defining the minimum amount of material that would need to be returned to Earth to fulfil the mission's principal scientific goals is an issue of paramount importance. If the only objective was to determine the $\Delta^{17}\text{O}$ composition of the venusian crust, then about 100 mg of material would probably suffice. High-precision laser fluorination analysis is normally undertaken on aliquots of approximately 2 mg and a return sample size of about 100 mg would ensure that the material could be adequately characterised for major and trace elements, as well as providing for multiple oxygen isotope analyses to be performed at a number of laboratories.

However, as set out below, a wide range of analytical techniques should also be used on these precious materials in order to glean as much information as possible about the origin and evolution of Venus. In other words, and within reason, the more material you can bring back, the more techniques you can apply and consequently the more you are likely to learn about Venus. In Table 2 an estimate is given of the sample mass required for a series of techniques that might be undertaken on a returned sample. Based on these estimates a sample mass of 9.4 g would be enough to provide very detailed information about the age and composition of the venusian lithosphere. The list of techniques given in Table 2 is far from exhaustive, but serves to demonstrate that a considerable amount of scientific data could be collected on an approximately 10 g sample. In fact, the allowances assigned to each of the techniques listed in Table 2 are on the generous side and by careful curation management the required amount of material could be reduced considerably. Thus, a 10 g nominal sample mass can accommodate all the essential techniques required to characterise the returned material.

However, bringing back just enough material to undertake measurements as they exist at the time of the mission does not provide any legacy for future generations. One of the great successes of the Apollo program was that a very large amount of material was returned from the Moon, with a significant fraction kept in clean conditions for future scientists to work on. Just defining a sample size on the basis of current constraints is not a good long-term strategy. Consequently, the question about how much material needs to be returned to Earth can be reconfigured based on engineering and budgetary perspectives to: how much material can be collected from the surface of Venus within "reasonable" cost and logistic constraints? One way to address this issue is to look at other sample return missions.

Between 1970 and 1976 the Soviet Union launched three successful remote sampling missions to the lunar surface (Luna 16, Luna 20 and Luna 24) (Robinson et al. 2012). Luna 16 returned a 35 cm-long core sample with an approximate mass of 101 g, Luna 20 returned 52 g of material and Luna 24 returned a 160 cm-long core containing 170 g of material (Robinson et al. 2012). While the logistics of returning a sample from the Moon are much less complex than would be the case for Venus, the Luna missions do at least demonstrate that remote sampling of a large-sized planetary body is a realistic option. The Luna 24 mission made use of a rotary percussion corer, demonstrating that such technology is a viable way to collect a large-sized sample from a planetary surface. Tests with a similar type

Table 2 Sample mass estimates for various analytical techniques

Method	Sample mass	Example study [@]
Initial characterisation		
4 × 1 cm ² polished sections	1.2 g	Stephant et al. (2019)
ICP-MS (major and traces) [*]	1.0 g	Barrat et al. (2016)
Dating studies		
Sm-Nd, Lu-Hf, Pb-Pb	2.5 g	Bouvier et al. (2008)
Mn-Cr (bulk)	0.1 g	Trinquier et al. (2008)
Mn-Cr (minerals)	0.5 g	Trinquier et al. (2008)
Rb-Sr	0.5 g	Shih et al. (2005)
In situ dating (SIMS)	Polished sections	Bellucci et al. (2015), Stephant et al. (2019)
Stable isotope analyses		
H isotopes bulk ^{**}	0.1 g	Alexander et al. (2012)
C isotopes bulk ^{**}	0.1 g	Alexander et al. (2012)
N isotopes bulk ^{**}	0.1 g	Alexander et al. (2012)
O isotopes bulk ^{**}	0.1 g	Greenwood et al. (2017, 2018b)
S isotopes bulk	0.5 g	Franz et al. (2014)
In situ stable isotopes	polished sections	Stephant et al. (2019)
Ti Cr isotopes [*]		
Cr	0.1 g	Bonnand et al. (2016)
Ti	0.1 g	Goodrich et al. (2017)
Mo Ru isotopes		
Ru	1.0 g	Hopp et al. (2020)
Mo	1.0 g	Hopp et al. (2020)
Highly siderophile elements (HSE) [*]		
HSE and Re-Os isotopes	0.5 g	Dhaliwal et al. (2017)
Total	9.4 g	

[@] Example studies are given to show how the quoted amount of material has been used as part of an analogous extraterrestrial study

^{*} Mass will allow multiple complete reruns at different labs

^{**} Sample masses shown are what is generally considered to be a representative fraction. The amount of material consumed for each individual replicate is considerably less than 100 mg and so these sample masses should allow for reruns at different labs

of drill designed to operate on Venus showed that it could core to a depth of 4.5 cm in 9.5 minutes and was able to recover 25 g of material (Rehnmark et al. 2017). Due to Venus' hostile surface conditions the collection phase of the sample return mission would have to be of short duration, perhaps no more than about an hour in total. Using a combination of drilling and surface grabbing (see Sect. 4.3.1), it would seem feasible to obtain at least 50 g of material. This would certainly be sufficient to allow all the analytical techniques outlined in Sect. 5 and Table 2 to be undertaken.

A number of other remote sample collection missions have been undertaken and have successfully returned extraterrestrial material to Earth. These include NASA's Stardust mission to Comet Wild 2 (Brownlee 2014), NASA's Genesis mission to collect solar wind ma-

terial (Jurewicz et al. 2003) and JAXA's Hayabusa mission to asteroid Itakowa (Nakamura et al. 2013). While these missions returned extremely limited amounts of material, they clearly demonstrate that major scientific breakthroughs can be achieved, even with very small samples (e.g. Matzel et al. 2010; McKeegan et al. 2011; Jin and Bose 2019). Current asteroid sample return missions OSIRIS-REx (Lauretta et al. 2017) and Hayabusa2 (Watanabe et al. 2017) are planning to return > 60 g and > 1 g of surface materials from asteroids Bennu and Ryugu, respectively. Even with the more limited amounts of material likely to be returned by Hayabusa2 from asteroid Ryugu, a full suite of isotopic and geochemical studies are envisaged (Watanabe et al. 2017). This again suggests that return of a 10 g nominal sample from Venus would provide sufficient material to support an ambitious analytical campaign. However, from a technical standpoint, there seems no reason why a much larger amount of material, for example 100 g, could not be returned from Venus. Such a sample size would provide both for immediate analytical work and also serve as a longer-term resource. It is worth noting again (see Sect. 4.1) that the ESA Venus sample return study (Coradini et al. 1998) envisaged a return mass of 300 g, consisting of 100 g of rock, 100 g of unconsolidated soil and 100 g of surface atmosphere.

Due to the likelihood that surface samples will have interacted, at least to some extent, with the harsh venusian atmosphere (Sect. 3.3), it is important that a surface atmospheric sample is collected to define the degree of atmosphere-lithosphere oxygen isotope disequilibrium. In addition, aliquots of gas could also be collected at higher levels in the atmosphere during either the lander ascent or descent phases. As a consequence of the high atmospheric pressures that prevail close to the surface of Venus, sampling adequate amounts of gas for high-precision oxygen and carbon analysis back on Earth would be relatively straightforward and requires only sample tanks of moderate volume. Thus, a 1 dm³ collection tank at the surface would passively collect about 1.5 moles of atmosphere (~65 g). This quantity of gas would be more than sufficient for a very large number of high-precision carbon, oxygen and nitrogen analyses using gas source mass spectrometry.

4.3 How Would We do a Sample Return Mission to Venus?

Retrieving samples from the surface of Venus and successfully returning them to Earth would be a technically challenging project and as a consequence relatively expensive to implement. However, while Venus represents an extremely hostile environment in which to operate a spacecraft, it has a mission failure rate that is not significantly different to that for Mars (sect. 1.1). In addition, many of the required technologies for sample return have already been tried and tested during past missions to Venus (Rodgers et al. 2000; Basilevsky et al. 2007; Dolgoplov et al. 2012; Rehnmark et al. 2017; Shibata et al. 2017; Glaze et al. 2018; Wilson et al. 2019). Here we outline two possible strategies to acquire and return surface samples from Venus. The first, and lower cost mission configuration, involves a lander with, or without, an orbiter, to transport the sample back to Earth. The second, more costly scenario, would be as part of an integrated mission to study in detail the atmosphere of Venus, but with a subsidiary lander to collect a small surface sample.

4.3.1 A “Grab and Go” Sample Return Scenario

Coradini et al. (1998) and Rodgers et al. (2000) provide scenarios outlining how a “Grab and Go” venusian sample return mission might be accomplished. The two studies share many features in common and so the summary scenario presented here is a composite derived from these earlier proposals. A schematic diagram summarising the various stages of the

mission are given in Fig. 14. The spacecraft would be two part, comprising an orbiter-return module and a lander-ascent stage. The full payload would be delivered to Venus by a single conventional launch, as proposed by Rodgers et al. (2000). Aerocapture by Venus could be facilitated by the use of a ballute, a hybrid of a balloon and parachute. A subsequent aerobraking manoeuvre would then put the spacecraft into a final equatorial and circular orbit.

Subsequent to orbital insertion, the lander would detach from the orbiter, with its velocity reduced using a small rocket motor. It would descend to the surface in about 1.5 hours. The dense venusian lower atmosphere facilitates a slow descent onto the surface and this would be further aided by the use of parachutes (Fig. 14). As proposed by Coradini et al. (1998), a limited number of atmospheric samples could be taken either during the descent or subsequent ascent stages. Once the lander reaches the surface, sampling would be undertaken rapidly using multiple methodologies, including drilling, scooping and possibly also a vacuum cleaner-type system (Fig. 14) (Coradini et al. 1998). Due to the high prevailing temperatures, surface operations would need to be conducted rapidly, probably lasting in total not much more than 1 hour. As discussed above, collection of a surface atmospheric sample would be an essential part of the mission in order to define the extent of oxygen isotopic disequilibrium between the atmosphere and lithosphere.

The initial ascent of the lander would be achieved using a helium balloon system, lifting the payload to a height of 66 km. A three-stage solid rocket system would then take the sample payload into orbit, where it would be captured by the orbiter. Return of the orbiter plus payload to Earth is a challenging procedure due to the large mass of Venus. A solar electric propulsion (SEP) system is preferred by Rodgers et al. (2000) over conventional chemical propulsion because of the large mass advantage of the SEP system (approximately 30%). Return of the sample payload to Earth would take about 3 years.

Significant advances have recently been made in sounding rocket technology, with the three stage JAXA SS-520-5 becoming the smallest rocket to place a satellite into Earth orbit in February 2018 (Graham 2018). The SS-520-5 measured 9.54 m and weighed 2600 kg. Incorporating a larger-sized sounding rocket within the lander module would have the potential to eliminate the need for a separate orbiter. Based on the mass estimates given by Rodgers et al. (2000), a single spacecraft incorporating a larger-sized sounding rocket within the lander assembly should weigh no more than about 5000 kg, which is slightly less than the Cassini spacecraft. Incorporating a rocket that could return the samples directly to Earth would eliminate the need for a potentially risky orbital rendezvous sample transfer manoeuvre.

4.3.2 An Extended Sample Return – Atmospheric Analysis Mission Scenario

A “Grab and Go” mission similar to that outlined by Rodgers et al. (2000) could also form part of an extended mission to study the atmosphere of Venus (Fig. 14). Wilson et al. (2019) have proposed a “strawman” L-class mission comprising an orbiter, cloud-level balloon platform and (optional) Russian-style descent probe. To facilitate sample return, the descent lander would need to be configured along the lines suggested by Rodgers et al. (2000). This mission could involve the collection of a comprehensive suite of atmospheric samples. As discussed in Sect. 5.3, there is a possibility that life may be present on Venus within the cloud layer at altitudes of between 51 km (65 °C) and 62 km (–20 °C) (Dartnell et al. 2015). This could be tested by returning atmospheric samples collected at the appropriate altitude.

Atmospheric data could also be collected remotely using a balloon platform, with the data transferred to the orbiter. In this case only the surface sample would be returned to Earth. In

view of current concerns about global warming there can be no doubt that a combined atmospheric and surface return mission would have a higher profile than just a surface sample collection mission with limited atmospheric sampling, as outlined in Sect. 4.3.1 above.

4.4 How Much Would it Cost?

Rodgers et al. (2000) estimate that a Venus sample return mission would require a budget in excess of a NASA Discovery mission, but would cost significantly less than Flagship missions. Most NASA Discovery missions fall in a cost range of between 300 and 800 million dollars, whereas recent Flagship missions to Mars, such as Mars 2020 or Mars Science Laboratory are in the 2 to 2.5 billion dollar cost bracket. On this basis we could put a tentative cost for a Venus “Grab and Go” sample return mission at about 1.5 billion dollars. A more extensive mission, involving a significant atmospheric sampling program would clearly be more expensive. Exactly how much more such a mission would cost would be dependent on the exact range of additional analytical tasks that were undertaken. As a guide, the NASA Venus Flagship Study Report (Venus Science & Technology Definition Team 2009) details a range of possible architectures, with estimated costs that vary from 1.6 to 3 billion dollars. The recommended option for further detailed evaluation included an orbiter, two mid-level orbital platforms and two landers and had an estimated cost of 2.7 billion dollars. On this basis 1.5 billion dollars for a “Grab and Go” mission seems generally realistic. In view of the importance of the science case for sample return from Venus, and despite the relatively high costs involved, such a mission ought to be given a very high priority.

An important additional consideration is the accumulating financial disparity between research on Mars compared to that on Venus. With a significant long-term program and extensive on-going activities, the budget for Mars research now dwarfs that for Venus. However, it is far from clear that this disparity can be justified from a scientific perspective. Mars is not a good analogue planet for Earth and its formation and early evolution are not representative of those that built the larger terrestrial planets, such as Earth and Venus. In contrast, Venus and Earth appear to have formed in closely similar ways. The more we learn about Venus, the more we learn about Earth (Wilson et al. 2019). From a scientific perspective the balance of funding needs to be redressed and research on Venus should be given significantly more emphasis than it is at present (Glaze and Garvin 2018; Wilson et al. 2019).

5 The Analytical Campaign Following Venus Sample Return

5.1 Overview

In view of the scientific value of returned samples from Venus, the analytical campaign following return to Earth would be a major undertaking and require detailed planning and preparation. This program would have the advantage of drawing on the experience gained from the lunar, Stardust and Hayabusa missions and hopefully also from Hayabusa2 and OSIRIS REX. In addition, the detailed planning that has been carried out for Mars sample return should provide a template for designing the necessary analytical protocols and strategies (Mars Exploration Program Analysis Group (MEPAG), 2012). In fact we would envisage the Venus sample analysis campaign following a very similar strategy to that outlined for Mars.

5.2 Clean Receiving Facility and Initial Handling Procedures

An important and critical component of the analytical program would be the development of a clean receiving laboratory. This might not necessarily be a brand new facility, but it would need to have been totally isolated and purged of any potential sources of terrestrial contamination prior to the return of actual Venus samples. Using analogue materials, appropriate protocols would need to be developed in order to establish initial characterisation and manipulation procedures. However, the experience gained from previous sample return campaigns should help to streamline this development process (Mars Exploration Program Analysis Group (MEPAG), 2012).

As envisaged for the return of martian material, samples from Venus would need to be initially screened using a non-invasive and non-destructive technique, such as X-ray computed tomography (XCT) (Welzenbach et al. 2019). This would potentially provide significant benefits in establishing the three-dimensional structure and textural variation of the returned materials, which would be of assistance in planning subsequent phases of the analytical campaign. However, there have been recent suggestions that XCT can cause permanent changes to sample materials (Sears et al. 2018) and so further evaluation of this technique is required (Welzenbach et al. 2019).

5.3 Planetary Protection Issues

From a planetary protection perspective, spacecraft operations in the venusian environment are currently classified as category II by the Committee on Space Research (COSPAR). This category covers: “All types of missions (gravity assist, orbiter, lander) to a target body where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could compromise future investigations” (COSPAR 2019). Compared to operations on Mars (category III – IV), the harsh venusian environment clearly poses less of a threat in terms of both forward and backward contamination. Samples collected from the upper regolith layers of Venus are unlikely to contain a viable biological component and should an organism be transported by the spacecraft from Earth it would not be viable in such an environment.

Despite the relatively low level of threat posed by Venus, prudence dictates that planetary protection issues would need to be taken seriously as part of the planning and preparation for a sample return mission. It now appears likely that Venus possessed surface conditions favourable for life in the past and these conditions may have persisted until as little as 700 Myr ago (Way et al. 2016). If life did evolve on Venus then it may still persist in various niche environments. It is theoretically possible that extremophiles could be present close to the venusian surface, at a minimum depth of about 10 m, where temperatures could be as low as 200 °C (Joseph 2019). However, due to time constraints, drill coring operations are unlikely to penetrate more than a few tens of centimetres below the surface.

The need for planetary protection is more acute for any atmospheric samples, in view of the theoretical possibility that life could be present within the lower cloud layer on Venus (Limaye et al. 2018). Based on a combination of temperature and pH constraints, Dartnell et al. (2015) estimated that extremophiles could live at altitudes of between 51 km (65 °C) and 62 km (–20 °C). The threat from such organisms may not just arise during atmospheric sampling activities. If the spacecraft and any collected materials are not properly protected, contamination could take place during the ascent phase following surface operations. There is also the possibility of forward contamination during the descent phase and so spacecraft build operations would need to be undertaken using protocols that minimised this threat.

5.4 Initial Classification and Characterisation Studies

Either with or without the use of XCT, initial characterisation work would start with the controlled removal of the samples from their enclosing collection containers, followed by weighing and initial imaging. This work would need to be undertaken based on the best practice approaches developed for other extraterrestrial sample suites (Allen et al. 2011). Suitable sub-samples would then need to be selected and prepared for mineralogical and petrographic study. This would involve the preparation of polished sections and grain mounts. These would be used to determine the textural and lithological diversity present in the samples using microbeam and related analysis techniques (quantitative scanning electron microscopy, electron microprobe, transmission electron microscopy). Other techniques that might be employed in these initial stages include: Raman spectroscopy, atomic force spectroscopy, ultraviolet-visible-near infrared (UV-Vis-NIR) microscopy, Electron Backscatter Diffraction (EBSD) and cathodoluminescence.

5.5 Bulk Major-Element, Trace-Element and Isotopic Analysis

As is the case for terrestrial, lunar and martian samples, bulk major- and trace-element analysis, generally now undertaken by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and related techniques (Jenner et al. 1990), would provide important constraints on the origin and evolution of returned samples from Venus. However, prior to crushing and dissolution for ICP-MS, cut surfaces of samples can first be studied by micro X-ray Fluorescence (μ XRF) scanning techniques. Secondary Ion Mass Spectrometry (SIMS) and Laser Ablation-Inductively Coupled Plasma-Mass Spectrometer (LA-ICP-MS) are in situ techniques that have been successfully employed in the study of martian meteorites (e.g. Lorand et al. 2018; Ireland et al. 2020) and would also have distinct advantages for the analysis of returned venusian samples. In addition, bulk isotopic data, particularly for Cr, Ti, Ni, W, Ca and Mo would permit a comparison between Venus and other Solar System bodies (Warren 2011; Scott et al. 2018). This data would be relevant to the proposition that Venus formed from essentially identical precursor material to that of the Earth (Sects. 2.3 and 2.4).

5.6 Stable Isotope Analysis

In this article we have highlighted the importance of undertaking oxygen isotope analysis of returned venusian samples. However, other stable isotope measurements (hydrogen, carbon, nitrogen, sulphur) would also yield critical information relevant to the evolution of Venus' early hydrosphere, lithosphere and atmosphere. Hydrogen isotope analysis would be particularly informative concerning the fate of water on Venus and surface sample measurements would be helpful in interpreting any data collected during atmospheric analysis (Grinspoon 2017). The venusian atmosphere contains very little water (about 30 ppm) and has a D/H ratio about 150 times higher than the oceans on Earth (Greenwood et al. 2018a). Based on the high D/H ratio, it has been suggested that Venus once contained similar amounts of water to Earth, but that this was subsequently lost to space (Donahue et al. 1982). D/H measurements of material collected from the tessera terrains would be particularly important in view of recent suggestions that these may have formed in the presence of surface water (Mueller et al. 2017). In terms of its carbon and nitrogen isotopic composition, Venus appears to have similar values to Earth (Greenwood et al. 2018a). High levels of relatively unstable sulphur species in the atmosphere of Venus may be due to ongoing volcanic replenishment mechanisms (Greenwood et al. 2018a). However, it has also been suggested that Venus is

significantly less active volcanically than Earth (Mikhail and Heap 2017). Combining the information obtained by stable isotope analysis of both returned surface and atmospheric samples from Venus should allow, for the first time, the development of quantitative circulation models for the planet and so constrain the nature of the ongoing interactions between its mantle, crust and atmosphere (Taylor et al. 2018).

5.7 The Importance of Dating Studies

Dating studies undertaken on the returned samples would be particularly important in view of the fact that there is currently no data relevant to the absolute ages of the various terrains identified on Venus (Taylor et al. 2018). Significant information is available on the relative ages of these surface units (Taylor et al. 2018) and there is general agreement that the tessera terrains represent the oldest exposed lithologies on the planet (e.g. Whitten and Campbell 2019). As discussed in Sect. 3.3, sample return from a tessera terrain would be valuable, although there is a significant risk that such ancient regions have experienced protracted surface-atmosphere interactions. Dating studies of returned tessera material should provide ages for the oldest geological events recorded by extant venusian rocks. Depending on the results, this data would help to constrain the likely tectonic regime on Venus. For example, do the tessera terrains represent continental crust as old as that on Earth or are they something completely different? A significant amount of comparative geology has already been undertaken for Venus using remote sensing data (Basilevsky et al. 2007). The dating of just one sample from the surface of Venus would help to place this information into a comparative context and would as a result enormously increase the value of the datasets already available. It is generally suggested that plate tectonics does not operate on Venus, but the manner in which the planet loses its heat is poorly constrained (Taylor et al. 2018). Dating of a single surface sample would certainly help to clarify significantly this important issue.

5.8 Noble Gas Analysis

Glaze and Garvin (2018) and Wilson et al. (2019) have highlighted the need for a complete suite of noble gas measurements to be made during sampling of the venusian atmosphere. As is the case for Earth and Mars, this data would help constrain any episodes of major degassing and atmospheric blow-off (Wilson et al. 2019). It would also be important to undertake such noble gas measurements on returned surface samples, which would then provide a basis for comparison with similar data from Earth and Mars (Peron et al. 2018; Ott et al. 2019).

5.9 Other Analysis Techniques

In addition to those outlined above, a wide range of other techniques could be used to interrogate samples returned from the surface of Venus. In particular, synchrotron-based techniques such as X-ray Absorption Near Edge Spectroscopy (XANES) would be useful in identifying the different oxidation states of species present in the samples (e.g. Nakada et al. 2019), while high-resolution X-ray diffraction studies would provide detailed structural information (e.g. Hicks et al. 2014). In addition, there is no doubt that new analytical techniques are likely to be available by the time samples from Venus are available for terrestrially-based researchers!

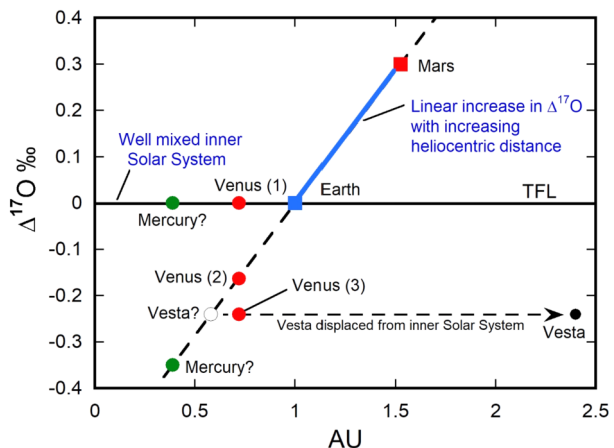
6 Some Final Thoughts and Speculations

While it is not possible to predict the $\Delta^{17}\text{O}$ composition of the returned venusian rock samples, we can at least examine the possible implications of various end-member scenarios (Fig. 15). A well-mixed, essentially homogeneous inner Solar System should lead to a venusian lithosphere with a $\Delta^{17}\text{O}$ that is close to that of the Earth (point 1 in Fig. 15) with a $\Delta^{17}\text{O}$ composition of ~ 0 ‰. In such a homogenised inner Solar System, Mercury might also have a similar $\Delta^{17}\text{O}$ to Venus and Earth, leaving Mars as the odd man out. If this does turn out to be the correct scenario then it would have significant implications for our understanding of the Moon-forming giant impact. The impactor, Theia was likely to have been of inner Solar System origin (Dauphas et al. 2014; Dauphas 2017) and so also have a $\Delta^{17}\text{O}$ composition close to 0 ‰. As a consequence, a well-mixed inner Solar System would mitigate many of the isotopic objections to the classic giant impact model of Canup and Asphaug (2001).

As discussed in Sect. 2.6, it has often been suggested that $\Delta^{17}\text{O}$ may vary with heliocentric distance. Currently we have samples from only two of the four terrestrial planets. Using the $\Delta^{17}\text{O}$ values for Earth and Mars, a linear relationship with distance from the Sun (AU) can be used to predict the $\Delta^{17}\text{O}$ values for Venus (Fig. 15, point 2, $\Delta^{17}\text{O} = -0.16$ ‰) and Mercury ($\Delta^{17}\text{O} = -0.35$ ‰). If Venus had such a composition it would essentially put an end to the classic giant impact model for the origin of the Moon (Canup and Asphaug 2001) and instead provide strong evidence in favour of higher-energy impact scenarios (Greenwood et al. 2018b; Lock and Stewart 2017). Perhaps more significantly, it would suggest that terrestrial planet-building took place on a more localized scale than would be the case for a totally homogenised inner Solar System.

A third possibility is that the $\Delta^{17}\text{O}$ composition of Venus doesn't have a value close to zero, nor does it fall on any simple linear mixing line. This would imply that building terrestrial planets may be a relatively chaotic process, particularly during the final "giant impact" stage (Walsh and Levison 2019). Even if the $\Delta^{17}\text{O}$ composition of Venus appears to be unrelated in any straightforward way to its neighbouring planets, surprises are still possible. As depicted in Fig. 15, Venus might turn out to have a $\Delta^{17}\text{O}$ value of -0.24 ‰, essentially identical to that of Vesta (Greenwood et al. 2017; Ireland et al. 2020). It was suggested by Bottke et al. (2006) that Vesta may be a main belt "interloper", scattered into its present position from a location within the terrestrial planet region. In addition, Vesta is

Fig. 15 Speculative Venus $\Delta^{17}\text{O}$ compositions based on different models for the formation of the inner Solar System. See Sect. 6 for further discussion



highly alkali-depleted and has a potassium isotopic composition ($\delta^{41}\text{K} = +0.36 \pm 0.16\%$) that is even heavier than the Moon (Tian et al. 2019). In the case of the Moon, its heavy potassium isotopic composition compared to terrestrial values was explained by Wang and Jacobsen (2016) as being the result of partial condensation from vapour in the aftermath of the giant impact. Vesta may represent a natural satellite that formed in a similar way to the Moon and was later displaced from its companion planet. It is possible that Vesta originally formed as a moon of Venus. Although this scenario is speculative, it remains unclear why Venus has no natural satellite, whereas the Earth does. It has been suggested that this reflects loss of an earlier-formed moon due to close encounters with other bodies (Brooks and Jacobson 2019).

7 Conclusions

In this paper we have highlighted the scientific imperative for determining the $\Delta^{17}\text{O}$ composition of Venus. This single measurement has the potential to radically change our understanding of how the early Solar System evolved. In particular, it would provide answers to the question: How well-mixed was the terrestrial planet region? If the Earth and Venus prove to be isotopic clones it could potentially alter our understanding of such events as the Moon-forming giant impact. There is already clear evidence that the early Solar System was bimodal in composition. A returned sample from Venus would be indispensable in studying and quantifying this phenomena.

In addition to this oxygen isotope data, a returned sample from the surface of Venus would also furnish a wealth of scientific information relevant to the evolution of the inner Solar System. Analysis of samples from Venus would deepen our understanding of comparative planetology, providing a firm basis for assessing similarities and differences with the evolution of early-Earth and Mars. In a wider context, analysis of returned samples from Venus will provide data relevant to the study of exoplanetary systems. Our Solar System provides us with an important case study in how two almost identical bodies, Earth and Venus, could have had such a divergent evolution. Finally, Venus, with its runaway greenhouse atmosphere, may provide data relevant to the understanding of similar less extreme processes on Earth. Venus is Earth's planetary twin and deserves to be better studied and understood. While humans will probably never set foot on its surface, this is not a good reason for neglecting the scientific study of such an important and nearby planet.

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References

- J. Alday, C.F. Wilson, P.G.J. Irwin, K.S. Olsen, L. Baggio, F. Montmessin, A. Trokhimovskiy, O. Korablev, A.A. Fedorova, D.A. Belyaev, A. Grigoriev, A. Patrakeev, A. Shakun, Oxygen isotopic ratios in Martian water vapour observed by ACS MIR on board the ExoMars Trace Gas Orbiter. *Astron. Astrophys.* **630**, A91 (2019). <https://doi.org/10.1051/0004-6361/201936234>
- C.M.O.D. Alexander, R. Bowden, M.L. Fogel, K.T. Howard, C.D.K. Herd, L.R. Nittler, The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science* **337**, 721–723 (2012). <https://doi.org/10.1126/science.1223474>
- Y. Alibert, J. Venturini, R. Helled, S. Ataiee, R. Burn, L. Senecal, W. Benz, L. Mayer, C. Mordasini, S.P. Quanz, M. Schönbachler, The formation of Jupiter by hybrid pebble-planetesimal accretion. *Nat. Astron.* **2**, 873–877 (2018). <https://doi.org/10.1038/s41550-018-0557-2>
- C. Allen, J. Allton, G. Lofgren, K. Righter, M. Zolensky, Curating NASA's extraterrestrial samples—past, present, and future. *Chem. Erde* **71**, 1–20 (2011). <https://doi.org/10.1016/j.chemer.2010.12.003>
- I. Angelo, J.F. Rowe, S.B. Howell, E.V. Quintana, M. Still, A.W. Mann, B. Burningham, T. Barclay, D.R. Ciardi, D. Huber, S.R. Kane, Kepler-1649b: an exo-venus in the solar neighborhood. *Astron. J.* **153**(4), 162 (2017). <https://doi.org/10.3847/1538-3881/aa615f>
- J.A. Barrat, R.C. Greenwood, K. Keil, M.L. Rouget, J.S. Boesenberg, B. Zanda, I.A. Franchi, The origin of aubrites: evidence from lithophile trace element abundances and oxygen isotope compositions. *Geochim. Cosmochim. Acta* **192**, 29–48 (2016). <https://doi.org/10.1016/j.gca.2016.07.025>
- A.T. Basilevsky, G.E. McGill, Surface evolution of Venus exploring Venus as a terrestrial planet, in *Geophys. Monogr. Ser.*, vol. 176, ed. by L.W. Esposito, E.R. Stofan, T.E. Cravens (Am. Geophys. Union, Washington, 2007), pp. 23–43
- A.T. Basilevsky, M.A. Ivanov, J.W. Head, M. Aittola, J. Raitala, Landing on Venus: past and future. *Planet. Space Sci.* **55**, 2097–2112 (2007). <https://doi.org/10.1016/j.pss.2007.09.005>
- J.J. Bellucci, A.A. Nemchin, M.J. Whitehouse, J.F. Snape, P. Bland, G.K. Benedix, The Pb isotopic evolution of the Martian mantle constrained by initial Pb in Martian meteorites. *J. Geophys. Res., Planets* **120**, 2224–2240 (2015). <https://doi.org/10.1002/2015JE004809>
- J. Blum, Dust evolution in protoplanetary discs and the formation of planetesimals. What have we learned from laboratory experiments? *Space Sci. Rev.* **214**, 52 (2018). <https://doi.org/10.1007/s11214-018-0486-5>
- J-D. Bodéan, N.A. Starkey, S.S. Russell, I.P. Wright, I.A. Franchi, An oxygen isotope study of wark-lovering rims on type A CAIs in primitive carbonaceous chondrites. *Earth Planet. Sci. Lett.* **401**, 327–336 (2014). <https://doi.org/10.1016/j.epsl.2014.05.035>
- P. Bonnand, H.M. Williams, I.J. Parkinson, B.J. Wood, A.N. Halliday, Stable chromium isotopic composition of meteorites and metal–silicate experiments: implications for fractionation during core formation. *Earth Planet. Sci. Lett.* **435**, 14–21 (2016). <https://doi.org/10.1016/j.epsl.2015.11.026>
- W.F. Bottke, D. Nesvorný, R.E. Grimm, A. Morbidelli, D.P. O'Brien, Iron meteorites as remnants of planetesimals formed in the terrestrial planet region. *Nature* **439**, 821–824 (2006). <https://doi.org/10.1038/nature04536>
- A. Bouvier, J. Blichert-Toft, J.D. Vervoort, P. Gillet, F. Albarède, The case for old basaltic shergottites. *Earth Planet. Sci. Lett.* **266**, 105–124 (2008). <https://doi.org/10.1016/j.epsl.2007.11.006>
- R. Brasser, S.J. Mojzsis, The partitioning of the inner and outer Solar System by a structured protoplanetary disk. *Nat. Astron.* (2020). <https://doi.org/10.1038/s41550-019-0978-6>
- J. Brooks, S.A. Jacobson, Losing moons: the gravitational influence of close encounters on satellite orbits. AAS Division on Dynamical Astronomy meeting #50, id. 302.05. *Bull. Am. Astron. Soc.* **51**, 5 (2019). https://113qx216in8z1kdeyi404hgfwengine.netdna-ssl.com/wp-content/uploads/2019/06/dda50_abstracts.pdf#abs302.05
- D. Brownlee, The stardust mission: analyzing samples from the edge of the Solar System. *Annu. Rev. Earth Planet. Sci.* **42**, 179–205 (2014). <https://doi.org/10.1146/annurev-earth-050212-124203>
- G. Budde, C. Burkhardt, G.A. Brennecke, M. Fischer-Gödde, T.S. Kruijer, T. Kleine, Molybdenum isotopic evidence for the origin of chondrules and a distinct genetic heritage of carbonaceous and non-carbonaceous meteorites. *Earth Planet. Sci. Lett.* **454**, 293–303 (2016). <https://doi.org/10.1016/j.epsl.2016.09.020>
- T.H. Burbine, R.C. Greenwood, Exploring the Bimodal Solar System via Sample Return from the Main Asteroid Belt: The Case for Revisiting Ceres. *Space Sci. Rev.* (2020). <https://doi.org/10.1007/s11214-020-00671-0>
- C. Burkhardt, N. Dauphas, U. Hans, B. Bourdon, T. Kleine, Elemental and isotopic variability in Solar System materials by mixing and processing of primordial disk reservoirs. *Geochim. Cosmochim. Acta* **261**, 145–170 (2019). <https://doi.org/10.1016/j.gca.2019.07.003>

- P.K. Byrne, R.C. Ghail, M.S. Gilmore, S.E. Smrekar, A.H. Treiman, C.F. Wilson, S.C. Solomon, The exploration of Venus: current understanding and open questions, in *50th Lunar and Planetary Science Conference*. LPI Contribution, vol. 2132 (2019). Abstract 2853. <https://www.hou.usra.edu/meetings/lpsc2019/pdf/2853.pdf>
- R.M. Canup, E. Asphaug, Origin of the Moon in a giant impact near the end of the Earth's formation. *Nature* **412**, 708–712 (2001). <https://doi.org/10.1038/35089010>
- J.E. Chambers, Pebble accretion and the diversity of planetary systems. *Astrophys. J.* **825**, 63 (2016). <https://doi.org/10.3847/0004-637X/825/1/63>
- E. Chassefière et al., European Venus Explorer (EVE): an in-situ mission to Venus. *Exp. Astron.* **23**, 741–760 (2009). <https://doi.org/10.1007/s10686-008-9093-x>
- A. Chau, C. Reinhardt, R. Helled, J. Stadel, Forming Mercury by giant impacts. *Astrophys. J.* **865**, 35 (2018). <https://doi.org/10.3847/1538-4357/aad8b0>
- B-G. Choi, K.D. McKeegan, A.N. Krot, J.T. Wasson, Extreme oxygen-isotope compositions in magnetite from unequilibrated ordinary chondrites. *Nature* **392**, 577–579 (1998). <https://doi.org/10.1038/33356>
- R.N. Clayton, Self-shielding in the solar nebula. *Nature* **415**, 860–861 (2002). <https://doi.org/10.1038/415860b>
- R.N. Clayton, Oxygen isotopes in meteorites, in *Treatise on Geochemistry*, vol. 1, ed. by A.M. Davis (Elsevier, Amsterdam, 2003), pp. 129–142. <https://doi.org/10.1016/B0-08-043751-6/01063-X>
- R.N. Clayton, Meteorites and their parent asteroids. *Science* **313**, 1743–1744 (2006). <https://doi.org/10.1126/science.1133137>
- R.N. Clayton, T.K. Mayeda, Formation of ureilites by nebular processes. *Geochim. Cosmochim. Acta* **52**, 1313–1318 (1988). [https://doi.org/10.1016/0016-7037\(88\)90286-4](https://doi.org/10.1016/0016-7037(88)90286-4)
- R.N. Clayton, L. Grossman, T.K. Mayeda, A component of primitive nuclear composition in carbonaceous chondrites. *Science* **182**, 485–488 (1973). <https://doi.org/10.1126/science.182.4111.485>
- R.N. Clayton, N. Onuma, L. Grossman, T.K. Mayeda, Distribution of the pre-solar component in Allende and other carbonaceous chondrites. *Earth Planet. Sci. Lett.* **34**, 209–224 (1977). [https://doi.org/10.1016/0012-821X\(77\)90005-X](https://doi.org/10.1016/0012-821X(77)90005-X)
- I.I. Cleeves, E.A. Bergin, C.M.O'D. Alexander, F. Du, D. Graninger, K.I. Oberg, T.J. Harries, The ancient heritage of water ice in the Solar System. *Science* **345**, 1590–1593 (2014). <https://doi.org/10.1126/science.1258055>
- Committee on Space Research, The International Planetary Protection Handbook (2019). <http://pposs.org/planetary-protection-handbook/>
- M. Coradini, G. Scoon, J-P. Lebreton, Venus sample return: assessment study report. M. Coradini, G. Scoon, J.-P. Lebreton. [S.I.]: European Space Agency, 1998. ESA/(Observatory Publications) (1998)
- J.N. Cuzzi, R.C. Hogan, W.F. Bottke, Towards initial mass functions for asteroids and Kuiper Belt Objects. *Icarus* **208**, 518–538 (2010). <https://doi.org/10.1016/j.icarus.2010.03.005>
- L.R. Dartnell, T.A. Nordheim, M.R. Patel, J.P. Mason, A.J. Coates, G.H. Jones, Constraints on a potential aerial biosphere on Venus: I. Cosmic rays. *Icarus* **257**, 396–405 (2015). <https://doi.org/10.1016/j.icarus.2015.05.006>
- N. Dauphas, The isotopic nature of the Earth's accreting material through time. *Nature* **541**, 521–524 (2017). <https://doi.org/10.1038/nature20830>
- N. Dauphas, E.A. Schauble, Mass fractionation laws, mass-independent effects, and isotopic anomalies. *Annu. Rev. Earth Planet. Sci.* **44**, 709–783 (2016). <https://doi.org/10.1146/annurev-earth-060115-012157>
- N. Dauphas, C. Burkhardt, P. Warren, F-Z. Teng, Geochemical arguments for an Earth-like Moon-forming impactor. *Philos. Trans. R. Soc. Lond. A* **372**, 20130244 (2014). <https://doi.org/10.1098/rsta.2013.0244>
- J.K. Dhaliwal, J.M.D. Day, C.A. Corder, K.T. Tait, K. Marti, N. Assayag, P. Cartigny, D. Rumble III., L.A. Taylor, Early metal-silicate differentiation during planetesimal formation revealed by acapulcoite and lodranite meteorites. *Geochim. Cosmochim. Acta* **216**, 115–140 (2017). <https://doi.org/10.1016/j.gca.2017.06.042>
- V.P. Dolgoplov, K.M. Pichkhadze, K.G. Sukhanov, The Vega Project: a space mission to Venus and Halley's comet. *Space Sci. Rev.* **46**, 568–577 (2012). <https://doi.org/10.1134/S0038094612070106>
- T.M. Donahue, J.H. Hoffman, R.R. Hodges, A.J. Watson, Venus was wet—a measurement of the ratio of deuterium to hydrogen. *Science* **216**, 630–633 (1982). <https://doi.org/10.1126/science.216.4546.630>
- P. Driscoll, D. Bercovici, Divergent evolution of Earth and Venus: influence of degassing, tectonics, and magnetic fields. *Icarus* **226**, 1447–1464 (2013). <https://doi.org/10.1016/j.icarus.2013.07.025>
- J. Farquhar, M.H. Thieme, T. Jackson, Atmosphere-surface interactions on Mars: $\Delta^{17}\text{O}$ measurements of carbonate from ALH 84001. *Science* **280**, 1580–1582 (1998). <https://doi.org/10.1126/science.280.5369.1580>
- G. Feulner, The faint young Sun problem. *Rev. Geophys.* **50**, RG2006 (2012). <https://doi.org/10.1029/2011RG000375>

- I.A. Franchi, Oxygen isotopes in asteroidal materials. *Rev. Miner.* **68**, 345–397 (2008). <https://doi.org/10.2138/rmg.2008.68.13>
- H.B. Franz, S.-T. Kim, J. Farquhar, J.M.D. Day, R.C. Economos, K.D. McKeegan, A.K. Schmitt, A.J. Irving, J. Hoek, J. Dottin III., Isotopic links between atmospheric chemistry and the deep sulphur cycle on Mars. *Nature* **508**, 364–368 (2014). <https://doi.org/10.1038/nature13175>
- J. Garvin, G. Arney, S. Getty, N. Johnson, W. Kiefer, R. Lorenz, M. Ravine, C. Malespin, C. Webster, B. Campbell, N. Izenberg, V. Cottini, DAVINCI+: deep atmosphere of Venus investigation of noble gases, chemistry and imaging, plus, in *51st Lunar Planet. Sci. Conf.* (2020). Abstract number 2599. <https://www.hou.usra.edu/meetings/lpsc2020/pdf/2599.pdf>
- R. Ghail, Rheological and petrological implications for a stagnant lid regime on Venus. *Planet. Space Sci.* **113–114**, 2–9 (2015). <https://doi.org/10.1016/j.pss.2015.02.005>
- R. Ghail, C. Wilson, T. Widemann, L. Bruzzzone, C. Dumoulin, J. Helbert, R. Herrick, E. Marcq, P. Mason, P. Rosenblatt, A. Carine Vandaele, L.-J. Burtz, EnVision: understanding why our most Earth-like neighbour is so different (2017). Eprint [arXiv:1703.09010](https://arxiv.org/abs/1703.09010)
- M. Gilmore, A. Treiman, J. Helbert, S. Smrekar, Venus surface composition constrained by observation and experiment. *Space Sci. Rev.* **212**, 1511–1540 (2017). <https://doi.org/10.1007/s11214-017-0370-8>
- M.S. Gilmore, J.L. Whitten, R. Perkins, J.F. Brossier, The ancient environments of Venus as recorded by Tessera terrain, in *American Geophysical Union, Fall Meeting 2019* (2019). Abstract #P51G-3445. <https://ui.adsabs.harvard.edu/abs/2019AGUFM.P51G3445G/abstract>
- L.S. Glaze, J.B. Garvin, Exploring Venus: never give up, never surrender, in *49th Lunar and Planetary Science Conference*. LPI Contribution, vol. 2083 (2018). Abstract 2024. <https://www.hou.usra.edu/meetings/lpsc2018/pdf/2024.pdf>
- L.S. Glaze, C.F. Wilson, L.V. Zasova, M. Nakamura, S. Limaye, Future of Venus research and exploration. *Space Sci. Rev.* **214**, 89 (2018). <https://doi.org/10.1007/s11214-018-0528-z>
- C. Goldblatt, A.J. Watson, The runaway greenhouse: implications for future climate change, geoengineering and planetary atmospheres. *Philos. Trans. R. Soc., Math. Phys. Eng. Sci.* **370**, 4197–4216 (2012). <https://doi.org/10.1098/rsta.2012.0004>
- C. Goodrich, D.P. O'Brien, Where did the ureilite parent body accrete? Constraints from chemical and isotopic compositions, in *American Astronomical Society, DPS Meeting #46, id. 304.03* (2014). <https://ui.adsabs.harvard.edu/abs/2014DPS....4630403G/abstract>
- C.A. Goodrich, N.T. Kita, Q.-Z. Yin, M.E. Sanborn, C.D. Williams, D. Nakashima, M.D. Lane, S. Boyle, Petrogenesis and provenance of ungrouped achondrite northwest Africa 7325 from petrology, trace elements, oxygen, chromium and titanium isotopes, and mid-IR spectroscopy. *Geochim. Cosmochim. Acta* **203**, 381–403 (2017). <https://doi.org/10.1016/j.gca.2016.12.021>
- W. Graham, Japanese sounding rocket claims record-breaking orbital launch. *NASASpaceflight.com* (2018). <https://www.nasaspaceflight.com/2018/02/japanese-rocket-record-orbital-launch/>
- R.C. Greenwood, T.H. Burbine, M.F. Miller, I.A. Franchi, Melting and differentiation of early-formed asteroids: the perspective from high precision oxygen isotope studies. *Chem. Erde* **77**, 1–43 (2017). <https://doi.org/10.1016/j.chemer.2016.09.005>
- J.P. Greenwood, S. Karato, K.E. Vander Kaaden, K. Pahlevan, T. Usui, Water and volatile inventories of Mercury, Venus, the Moon, and Mars. *Space Sci. Rev.* **214**, 92 (2018a). <https://doi.org/10.1007/s11214-018-0526-1>
- R.C. Greenwood, J.-A. Barrat, M.F. Miller, M. Anand, N. Dauphas, I.A. Franchi, P. Sillard, N.A. Starkey, Oxygen isotopic evidence for accretion of Earth's water before a high-energy Moon-forming giant impact. *Sci. Adv.* **4**, 5928 (2018b). <https://doi.org/10.1126/sciadv.aao5928>
- R.C. Greenwood, T.H. Burbine, I.A. Franchi, Linking asteroids and meteorites to the primordial planetesimal population. *Geochim. Cosmochim. Acta* (2020, in press). <https://doi.org/10.1016/j.gca.2020.02.004>
- T.K.P. Gregg, L. Zasova, T. Economou, N. Eismont, M. Gerasimov, D. Gorinov, N. Ignatiev, M. Ivanov, I. Khatuntsev, O. Korablev, T. Kremic, K. Jessup, S. Limaye, I. Lomakin, A. Martynov, A. Ocampo, Venera-D: a potential long-lived mission to explore Venus' surface, atmosphere and plasma environment, in *50th Lunar Planet. Sci. Conf.*. LPI Contrib., vol. 2132 (2019). Abstract number 1738. <https://www.hou.usra.edu/meetings/lpsc2019/pdf/1738.pdf>
- R.E. Grimm, H.Y. McSween Jr., Water and the thermal evolution of carbonaceous chondrite parent bodies. *Icarus* **82**, 244–280 (1989). [https://doi.org/10.1016/0019-1035\(89\)90038-9](https://doi.org/10.1016/0019-1035(89)90038-9)
- D.H. Grinspoon, The need for new in situ measurements to understand the climate, geology and evolution of Venus, in *American Geophysical Union, Fall Meeting* (2017). Abstract #P52A-08. <https://ui.adsabs.harvard.edu/abs/2017AGUFM.P52A..08G/abstract>
- B. Gundlach, J. Blum, The stickiness of micrometer-sized water-ice particles. *Astrophys. J.* **798**, 34 (2015). <https://doi.org/10.1088/0004-637X/798/1/34>
- J.H. Guo, The effect of photoionization on the loss of water of the planet. *Astrophys. J.* **872**, 99 (2019). <https://doi.org/10.3847/1538-4357/aaffd4>

- K.E. Haisch Jr., E.A. Lada, C.J. Lada, Disk frequencies and lifetimes in young clusters. *Astrophys. J. Lett.* **553**, L153 (2001). <https://doi.org/10.1086/320685>
- L.J. Hallis, M. Anand, R.C. Greenwood, M.F. Miller, I.A. Franchi, S.S. Russell, The oxygen isotope composition, petrology and geochemistry of mare basalts: evidence for large-scale compositional variation in the lunar mantle. *Geochim. Cosmochim. Acta* **74**, 6885–6899 (2010). <https://doi.org/10.1016/j.gca.2010.09.023>
- G.L. Hashimoto, M. Roos-Serote, S. Sugita, M.S. Gilmore, L.W. Kamp, R.W. Carlson, K.H. Baines, Felsic highland crust on Venus suggested by Galileo near-infrared mapping spectrometer data. *J. Geophys. Res.* **113**(E9), E00B24 (2008). <https://doi.org/10.1029/2008JE003134>
- L.J. Hicks, J.C. Bridges, S.J. Gurman, Ferric saponite and serpentine in the nakhlite martian meteorites. *Geochim. Cosmochim. Acta* **136**, 194–210 (2014). <https://doi.org/10.1016/j.gca.2014.04.010>
- T. Hopp, G. Budde, T. Kleine, Heterogeneous accretion of Earth inferred from Mo-Ru isotope systematics. *Earth Planet. Sci. Lett.* **534**, 116065 (2020). <https://doi.org/10.1016/j.epsl.2020.116065>
- T.R. Ireland, J. Avila, R.C. Greenwood, L.J. Hicks, J.C. Bridges, Oxygen isotopes and sampling of the Solar System. *Space Sci. Rev.* (2020). <https://doi.org/10.1007/s11214-020-0645-3>
- M.A. Ivanov, J.W. Head, Global geological map of Venus. *Planet. Space Sci.* **59**, 1559–1600 (2011). <https://doi.org/10.1016/j.pss.2011.07.008>
- S.A. Jacobson, D.C. Rubie, J. Herlund, A. Morbidelli, M. Nakajima, Formation, stratification, and mixing of the cores of Earth and Venus. *Earth Planet. Sci. Lett.* **474**, 375–386 (2017). <https://doi.org/10.1016/j.epsl.2017.06.023>
- M. Javoy, E. Kaminski, F. Guyot, D. Andraut, C. Sanloup, M. Moreira, S. Labrosse, A. Jambon, P. Agrinier, A. Davaille, C. Jaupart, The chemical composition of the Earth: enstatite chondrite models. *Earth Planet. Sci. Lett.* **293**, 259–268 (2010). <https://doi.org/10.1016/j.epsl.2010.02.033>
- G.A. Jenner, H.P. Longerich, E. Jackson, B.J. Fryer, ICP-MS — a powerful tool for high-precision trace-element analysis in Earth sciences: evidence from analysis of selected U.S.G.S. reference samples. *Chem. Geol.* **83**, 133–148 (1990). [https://doi.org/10.1016/0009-2541\(90\)90145-W](https://doi.org/10.1016/0009-2541(90)90145-W)
- Z. Jin, M. Bose, New clues to ancient water on Itokawa. *Sci. Adv.* **5**, 8106 (2019). <https://doi.org/10.1126/sciadv.aav8106>
- A. Johansen, M. Lambrechts, Forming planets via pebble accretion. *Annu. Rev. Earth Planet. Sci.* **45**, 359–387 (2017). <https://doi.org/10.1146/annurev-earth-063016-020226>
- R.G. Joseph, Life on Venus and the interplanetary transfer of biota from Earth. *Astrophys. Space Sci.* **364**(11), 191 (2019). <https://doi.org/10.1007/s10509-019-3678-x>
- A.J.G. Jurewicz et al., The genesis solar-wind collector materials. *Space Sci. Rev.* **105**, 535–560 (2003). <https://doi.org/10.1023/A:1024469927444>
- N.A. Kaib, N.B. Cowan, The feeding zones of terrestrial planets and insights into Moon formation. *Icarus* **252**, 161–174 (2015). <https://doi.org/10.1016/j.icarus.2015.01.013>
- G.W. Kallemeyn, A.E. Rubin, J.T. Wasson, The compositional classification of chondrites: VII. The R chondrite group. *Geochim. Cosmochim. Acta* **60**, 2243–2256 (1996). [https://doi.org/10.1016/0016-7037\(96\)88430-4](https://doi.org/10.1016/0016-7037(96)88430-4)
- S.R. Kane, A.J. Ceja, M.J. Way, E.V. Quintana, Climate modelling of a potential ExoVenus. *Astrophys. J.* **869**, 46 (2018). <https://doi.org/10.3847/1538-4357/aaec68>
- S.R. Kane, G. Arney, D. Crisp, S. Domagal-Goldman, L.S. Glaze, C. Goldblatt, D. Grinspoon, J.W. Head, A. Lenardic, C. Unterborn, M.J. Way, K.J. Zahnle, Venus as a laboratory for exoplanetary science. *J. Geophys. Res., Planets* **124**, 2015–2028 (2019). <https://doi.org/10.1029/2019JE005939>
- J.F. Kastning, J.B. Pollack, Loss of water from Venus. I - Hydrodynamic escape of hydrogen. *Icarus* **53**, 479–508 (1983). [https://doi.org/10.1016/0019-1035\(83\)90212-9](https://doi.org/10.1016/0019-1035(83)90212-9)
- S. Khawja, R.E. Ernst, C. Samson, P.K. Byrne, R.C. Ghail, Erosional features on tessera terrains Venus, in *51st Lunar Planet. Sci. Conf.* (2020). Abstract number 1161. <https://www.hou.usra.edu/meetings/lpsc2020/pdf/1161.pdf>
- T. Kodama, H. Genda, R. O’ishi, A. Abe-Ouchi, Y. Abe, Inner edge of habitable zones for Earth-sized planets with various surface water distributions. *J. Geophys. Res., Planets* **124**, 2306–2324 (2019). <https://doi.org/10.1029/2019JE006037>
- V.A. Krasnopolsky, D.A. Belyaev, I.E. Gordon, G. Li, L.S. Rothman, Observations of D/H ratios in H₂O, HCl, and HF on Venus and new DCI and DF line strengths. *Icarus* **224**, 57–65 (2013). <https://doi.org/10.1016/j.icarus.2013.02.010>
- A.N. Krot, Y. Amelin, P. Bland, F.J. Ciesla, J. Connelly, A.M. Davis, G.R. Huss, I.D. Hutcheon, K. Makide, K. Nagashima, L.E. Nyquist, S.S. Russell, E.R.G. Scott, K. Thrane, H. Yurimoto, Q-Z. Yin, Origin and chronology of chondritic components: a review. *Geochim. Cosmochim. Acta* **73**, 4963–4997 (2009). <https://doi.org/10.1016/j.gca.2008.09.039>
- A.N. Krot, K. Keil, E.R.D. Scott, C.A. Goodrich, M.K. Weisberg, Classification of meteorites and their genetic relationships, in *Meteorites and cosmochemical processes; Treatise on Geochemistry, vol. 1*, ed. by A.M. Davis 2nd edn. (Elsevier, Amsterdam, 2014), pp. 1–63

- T.S. Kruijjer, C. Burkhardt, G. Budde, T. Kleine, Thorsten Age of Jupiter inferred from the distinct genetics and formation times of meteorites. *Proc. Natl. Acad. Sci.* **114**, 6712–6716 (2017). <https://doi.org/10.1073/pnas.1704461114>
- T.S. Kruijjer, T. Kleine, L.E. Borg, The great isotopic dichotomy of the early Solar System. *Nat. Astron.* **4**, 32–40 (2020). <https://doi.org/10.1038/s41550-019-0959-9>
- M. Lambrechts, A. Johansen, Rapid growth of gas-giant cores by pebble accretion. *Astron. Astrophys.* **544**, A32 (2012). <https://doi.org/10.1051/0004-6361/201219127>
- D.S. Lauretta et al., Sample return from Asteroid (101955) Benu. *Space Sci. Rev.* **212**, 925–984 (2017). <https://doi.org/10.1007/s11214-017-0405-1>
- J. Leconte, F. Forget, B. Charnay, B. Wordsworth, A. Pottier, Increased insolation threshold for runaway greenhouse processes on Earth-like planets. *Nature* **504**, 268–271 (2014). <https://doi.org/10.1038/nature12827>
- S.J. Limaye, R. Mogul, D.J. Smith, A.H. Ansari, G.P. Słowik, P. Vaishampayan, Venus' spectral signatures and the potential for life in the clouds. *Astrobiology* **18**, 1181–1198 (2018). <https://doi.org/10.1089/ast.2017.1783>
- M-C. Liu, K.D. McKeegan, J.N. Goswami, K.K. Marhas, S. Sahijpal, T.R. Ireland, A.M. Davis, Isotopic records in CM hibonites: implications for timescales of mixing of isotope reservoirs in the solar nebula. *Geochim. Cosmochim. Acta* **73**, 5051–5079 (2009). <https://doi.org/10.1016/j.gca.2009.02.039>
- S.J. Lock, S.T. Stewart, The structure of terrestrial bodies: impact heating, corotation limits, and synestias. *J. Geophys. Res.* (2017). <https://doi.org/10.1002/2016JE005239>
- S.J. Lock, S.T. Stewart, M.I. Petaev, Z.M. Leinhardt, M. Mace, S.B. Jacobsen, M. Čuk, A new model for lunar origin: equilibration with Earth beyond the hot spin stability limit, in *LPSC*, vol. 47 (2016). Abstract #2881. <https://www.hou.usra.edu/meetings/lpsc2016/pdf/2881.pdf>
- K. Lodders, Solar system abundances and condensation temperatures of the elements. *Astrophys. J.* **591**, 1220–1247 (2003). <https://doi.org/10.1086/375492>
- J-P. Lorand, R.H. Hewins, M. Humayun, L. Remusat, B. Zanda, C. La, S. Pont, Chalcophile-siderophile element systematics of hydrothermal pyrite from martian regolith breccia NWA 7533. *Geochim. Cosmochim. Acta* **241**, 134–149 (2018). <https://doi.org/10.1016/j.gca.2018.08.041>
- J.R. Lyons, E.D. Young, CO self-shielding as the origin of oxygen isotope anomalies in the early solar nebula. *Nature* **435**, 317–320 (2005). <https://doi.org/10.1038/nature03557>
- J.R. Lyons, E.A. Bergin, F.J. Ciesla, A.M. Davis, S.J. Desch, K. Hashizume, J-A. Lee, Timescales for the evolution of oxygen isotope compositions in the solar nebula. *Geochim. Cosmochim. Acta* **73**, 4998–5017 (2009). <https://doi.org/10.1016/j.gca.2009.01.041>
- Mars Exploration Program Analysis Group, Planning for Mars returned sample science: final report of the MSR end-to-end international science analysis group (E2E-iSAG). *Astrobiology* **12**, 175–230 (2012). <https://doi.org/10.1089/ast.2011.0805>
- Y. Matsuhisa, J.R. Goldsmith, R.N. Clayton, Mechanisms of hydrothermal crystallization of quartz at 250°C and 15 kbar. *Geochim. Cosmochim. Acta* **42**, 173–182 (1978). [https://doi.org/10.1016/0016-7037\(78\)90130-8](https://doi.org/10.1016/0016-7037(78)90130-8)
- J.E.P. Matzel, H.A. Ishii, D. Joswiak, I.D. Hutcheon, J.P. Bradley, D. Brownlee, P.K. Weber, N. Teslich, G. Matrajt, K.D. McKeegan, G.J. MacPherson, Constraints on the formation age of cometary material from the NASA Stardust Mission. *Science* **328**, 483–486 (2010). <https://doi.org/10.1126/science.1184741>
- K.D. McKeegan, A.P.A. Kallio, V.S. Heber, G. Jarzebinski, P.H. Mao, C.D. Coath, T. Kunihiro, R.C. Wiens, J.E. Nordholt, R.W. Moses, D.B. Reisenfeld, A.J. Jurewicz, D.S. Burnett, The oxygen isotopic composition of the Sun inferred from captured solar wind. *Science* **332**, 1528–1532 (2011). <https://doi.org/10.1126/science.1204636>
- H.Y. McSween Jr., What we have learned about Mars from SNC meteorites. *Meteoritics* **29**(6), 757–779 (1994). <https://doi.org/10.1111/j.1945-5100.1994.tb01092.x>
- S. Mikhail, M.J. Heap, Hot climate inhibits volcanism on Venus: constraints from rock deformation experiments and argon isotope geochemistry. *Phys. Earth Planet. Inter.* **268**, 18–34 (2017). <https://doi.org/10.1016/j.pepi.2017.05.007>
- M.F. Miller, Isotopic fractionation and the quantification of ¹⁷O anomalies in the oxygen three-isotope system: an appraisal and geochemical significance. *Geochim. Cosmochim. Acta* **66**, 1881–1889 (2002). [https://doi.org/10.1016/S0016-7037\(02\)00832-3](https://doi.org/10.1016/S0016-7037(02)00832-3)
- M.F. Miller, A. Pack, I.N. Bindeman, R.C. Greenwood, Standardizing the reporting of $\Delta^{17}\text{O}$ data from high precision oxygen triple-isotope ratio measurements of silicate rocks and minerals. *Chem. Geol.* **532**, 119332 (2020). <https://doi.org/10.1016/j.chemgeo.2019.119332>
- A. Morbidelli, *Accretion Processes, Oxford Research Encyclopedia, Planetary Science* (Oxford University Press, USA, 2018). <https://doi.org/10.1093/acrefore/9780190647926.013.32>
- A. Morbidelli, M. Lambrechts, S. Jacobson, B. Bitsch, The great dichotomy of the Solar System: small terrestrial embryos and massive giant planet cores. *Icarus* **258**, 418–429 (2015). <https://doi.org/10.1016/j.icarus.2015.06.003>

- N.T. Mueller, C. Tsang, D.C. Nunes, J. Helbert, M.D. Dyar, S.E. Smrekar, Near infrared multispectral mapping of Venus supports the hypothesis that tessera plateau material was formed in the presence of surface water, in *American Geophysical Union, Fall Meeting 2017* (2017). Abstract #P53A-2645. <https://ui.adsabs.harvard.edu/abs/2017AGUFM.P53A2645M/abstract>
- R. Nakada, T. Usui, M. Ushioda, Y. Takahashi, Micro-Xanes determination of oxidation states of V and Fe in olivine-hosted glass inclusion and groundmass of Yamato 980459, in *Ninth International Conference on Mars*. LPI Contrib., vol. 2089 (2019). Abstract number 6133. <https://www.hou.usra.edu/meetings/ninthmars2019/pdf/6133.pdf>
- M. Nakamura, Venus Observation by Akatsuki: 2015–2019. EPSC Abstracts 13, EPSC-DPS2019-391-3 (2019). <https://meetingorganizer.copernicus.org/EPSC-DPS2019/EPSC-DPS2019-391-3.pdf>
- T. Nakamura et al., Itokawa dust particles: a direct link between S-type asteroids and ordinary chondrites. *Science* **333**, 1113–1116 (2013). <https://doi.org/10.1126/science.1207758>
- M. Nakamura et al., AKATSUKI returns to Venus. *Earth Planets Space* **68**, 75, 10 (2016). <https://doi.org/10.1186/s40623-016-0457-6>
- J.A.M. Nanne, F. Nimmo, J.N. Cuzzi, T. Kleine, Origin of the non-carbonaceous–carbonaceous meteorite dichotomy. *Earth Planet. Sci. Lett.* **511**, 44–54 (2019). <https://doi.org/10.1016/j.epsl.2019.01.027>
- National Space Policy of the United States of America (2010). https://history.nasa.gov/national_space_policy_6-28-10.pdf
- F. Nimmo, D. McKenzie, Volcanism and tectonics on Venus. *Annu. Rev. Earth Planet. Sci.* **26**, 23–53 (1998). <https://doi.org/10.1146/annurev.earth.26.1.23>
- E.G. Nisbet, N.H. Sleep, The habitat and nature of early life. *Nature* **409**, 1083–1091 (2001). <https://doi.org/10.1038/35059210>
- J.G. O'Rourke, C. Gillmann, P. Tackley, Prospects for an ancient dynamo and modern crustal remnant magnetism on Venus. *Earth Planet. Sci. Lett.* **502**, 46–56 (2018). <https://doi.org/10.1016/j.epsl.2018.08.055>
- U. Ott, T.D. Swindle, S.P. Schwenger, Chap. 3 - Noble Gases in Martian Meteorites: Budget, Sources, Sinks, and Processes in Volatiles in the Martian Crust (2019), pp. 35–70. <https://doi.org/10.1016/B978-0-12-804191-8.00003-9>
- A. Pack, D. Herwartz, The triple oxygen isotope composition of the Earth mantle and understanding $\Delta^{17}\text{O}$ variations in terrestrial rocks and minerals. *Earth Planet. Sci. Lett.* **390**, 138–145 (2014). <https://doi.org/10.1016/j.epsl.2014.01.017>
- S. Peron, M. Moreira, A. Agranier, Origin of light noble gases (He, Ne, and Ar) on Earth: a review. *Geochem. Geophys. Geosyst.* **9**, 979–996 (2018). <https://doi.org/10.1002/2017GC007388>
- E.V. Pitjeva, N.P. Pitjev, Masses of the Main Asteroid Belt and the Kuiper Belt from the motions of planets and spacecraft. *Astron. Lett.* **44**, 554–566 (2018). <https://doi.org/10.1134/S1063773718090050>
- Planetary Society website, Missions to Mars, Planetary Society (2020). <http://www.planetary.org/explore/space-topics/space-missions/missions-to-mars.html>
- L. Qin, C.M.O'D. Alexander, R.W. Carlson, M.F. Horan, T. Yokoyama, Contributions to chromium isotope variations of meteorites. *Geochim. Cosmochim. Acta* **74**, 1122–1145 (2010). <https://doi.org/10.1016/j.gca.2009.11.005>
- S.N. Raymond, A. Izidoro, Origin of water in the inner Solar System: planetesimals scattered inward during Jupiter and Saturn's rapid gas accretion. *Icarus* **297**, 134–148 (2017). <https://doi.org/10.1016/j.icarus.2017.06.030>
- F. Rehnmark, K. Zaczyn, J. Hall, E. Cloninger, C. Hyman, K. Kriechbaum, J. Melko, J. Rabinovitch, B. Wilcox, J. Lambert, N. Traeden, J. Bailey, Sample acquisition drill for Venus in situ explorer (VISE), in *48th Lunar and Planetary Science* (2017). Abstract number 1367. <https://www.hou.usra.edu/meetings/lpsc2017/eposter/1367.pdf>
- M.S. Robinson, J.B. Plescia, B.L. Jolliff, S.J. Lawrence, Soviet lunar sample return missions: landing site identification and geologic context. *Planet. Space Sci.* **69**, 76–88 (2012). <https://doi.org/10.1016/j.pss.2012.03.013>
- D. Rodgers, M. Gilmore, T. Sweetser, J. Cameron, G.-S. Chen, J. Cutts, R. Gershman, J.L. Hall, V. Kerzhanovich, A. McRonald, E. Nilsen, W. Petrick, C. Sauer, B. Wilcox, A. Yavrouian, W. Zimmerman, Venus sample return. A hot topic, in *Proc. IEEE Aerospace Conf.*, vol. 7 (2000), pp. 473–484. <https://trs.jpl.nasa.gov/bitstream/handle/2014/18501/99-1991.pdf?sequence=1>
- J.J.R. Rosman, P.D.P. Taylor, Isotopic compositions of the elements 1997. *Pure Appl. Chem.* **70**, 217–236 (1998). <https://doi.org/10.1351/pac199870010217>
- A.E. Rubin, J.T. Wasson, Variations of chondrite properties with heliocentric distance. *Meteoritics* **30**, 569 (1995) (abstract). <http://articles.adsabs.harvard.edu/pdf/1995Metic...30Q.569R>
- R.Z. Sagdeev, V.M. Linkin, J.E. Blamont, R.A. Preston, The VEGA Venus balloon experiment. *Science* **231**, 1407–1408 (1986). <https://doi.org/10.1126/science.231.4744.1407>
- N. Sakamoto, Y. Seto, S. Itoh, K. Kuramoto, K. Fujino, K. Nagashima, A.N. Krot, H. Yurimoto, Remnants of the early Solar System water enriched in heavy oxygen isotopes. *Science* **317**, 231–233 (2007). <https://doi.org/10.1126/science.1142021>

- E.R.D. Scott, A.N. Krot, I.S. Sanders, Isotopic dichotomy among meteorites and its bearing on the protoplanetary disk. *Astrophys. J.* **854**, 164 (2018). <https://doi.org/10.3847/1538-4357/aaa5a5>
- D.W.G. Sears, A. Sehlke, J.M. Friedrich, M.L. Rivers, D.S. Ebel, X-ray computed tomography of extraterrestrial rocks eradicates their natural radiation record and the information it contains. *Meteorit. Planet. Sci.* **53**, 2624–2631 (2018). <https://doi.org/10.1111/maps.13183>
- E.V. Shalygin, W.J. Markiewicz, A.T. Basilevsky, D.V. Titov, N.I. Ignatiev, J.W. Head, Active volcanism on Venus in the Ganiki Chasma rift zone. *Geophys. Res. Lett.* **42**, 4762–4769 (2015). <https://doi.org/10.1002/2015GL064088>
- E. Shibata, Y. Lu, A. Pradeepkumar, J.A. Cutts, S.J. Saika, A Venus atmospheric sample return mission concept: feasibility and technology requirements, in *Planetary Science Vision 2050 Workshop*. LPI Contribution, vol. 1981 (2017). Abstract 8164. <https://www.hou.usra.edu/meetings/V2050/pdf/8164.pdf>
- C-Y. Shih, L.E. Nyquist, H. Wiesmann, Y. Reese, K. Misawa, Rb-Sr and Sm-Nd dating of olivine-phyric shergottite Yamato 980459: petrogenesis of depleted shergottites. *Antarct. Meteor. Res.* **18**, 46–65 (2005) <http://adsabs.harvard.edu/full/2005AMR....18...46S>
- F.H. Shu, H. Shang, M. Gounelle, A.E. Glassgold, T. Lee, Typhoon. The origin of chondrules and refractory inclusions in chondritic meteorites. *Astrophys. J.* **548**(2), 1029–1050 (2001). <https://doi.org/10.1086/319018>
- S.E. Smrekar, A. Davaile, C. Sotin, Venus interior structure and dynamics. *Space Sci. Rev.* **214**, 88 (2018). <https://doi.org/10.1007/s11214-018-0518-1>
- S. Smrekar, S. Hensley, D. Dyar, J. Helbert, VERITAS (Venus Emissivity, Radio science, InSAR, Topography And Spectroscopy): a proposed discovery mission, in *EPSC-DPS Joint Meeting EPSC-DPS2019-1124* (2019). <https://meetingorganizer.copernicus.org/EPSC-DPS2019/EPSC-DPS2019-1124-1.pdf>
- M.L. Spicuzza, J.M.D. Day, L.A. Taylor, J.W. Valley, Oxygen isotope constraints on the origin and differentiation of the Moon. *Earth Planet. Sci. Lett.* **253**, 254–265 (2007). <https://doi.org/10.1016/j.epsl.2006.10.030>
- N.A. Starkey, I.A. Franchi, M.R. Lee, Isotopic diversity in interplanetary dust particles and preservation of extreme ¹⁶O-depletions. *Geochim. Cosmochim. Acta* **142**, 115–131 (2014). <https://doi.org/10.1016/j.gca.2014.07.011>
- A. Stephant, M. Anand, H.O. Ashcroft, X. Zhao, R.L. Korotev, S. Strelkopytovo, R.C. Greenwood, E. Humphreys-Williams, Y. Liu, G. Tang, Q. Li, I.A. Franchi, An ancient reservoir of volatiles in the Moon sampled by lunar meteorite Northwest Africa 10989. *Geochim. Cosmochim. Acta* **266**, 163–183 (2019). <https://doi.org/10.1016/j.gca.2019.07.045>
- D.J. Stevenson, Planetary magnetic fields. *Earth Planet. Sci. Lett.* **208**, 1–11 (2003). [https://doi.org/10.1016/S0012-821X\(02\)01126-3](https://doi.org/10.1016/S0012-821X(02)01126-3)
- D.J. Stevenson, A.N. Halliday, The origin of the Moon. *Philos. Trans. R. Soc. A* **372**, 20140289 (2014). <https://doi.org/10.1098/rsta.2014.0289>
- F.W. Taylor, *The Scientific Exploration of Venus* (Cambridge University Press, Cambridge, 2014)
- F.W. Taylor, J.P. Lebreton, G. Scoon, P. Logonne, P. Masson, H. Waelenke, M. Coradini, VSR and MSR study team ESA advanced planetary mission studies: Venus sample return and Mercury sample return, in *American Astronomical Society, DPS Meeting #31, id. 21.06* (1999). <http://adsabs.harvard.edu/full/1999BAAS...31.1108T>
- F.W. Taylor, H. Svedhem, J.W. Head, Venus: the atmosphere, climate, surface, interior and near-space environment of an Earth-like planet. *Space Sci. Rev.* **214**, 35 (2018). <https://doi.org/10.1007/s11214-018-0467-8>
- M.H. Thiemens, J.E. Heidenreich, The mass-independent fractionation of oxygen: a novel isotope effect and its possible cosmochemical implications. *Science* **219**, 1073–1075 (1983). <https://doi.org/10.1126/science.219.4588.1073>
- M.H. Thiemens, T.L. Jackson, C.A.M. Brenninkmeijer, Observation of a mass independent oxygen isotopic composition in terrestrial stratospheric CO₂, the link to ozone chemistry, and the possible occurrence in the Martian atmosphere. *Geophys. Res. Lett.* **22**, 255–257 (1995). <https://doi.org/10.1029/94GL02996>
- E.W. Thommes, M.J. Duncan, H.F. Levison, Oligarchic growth of giant planets. *Icarus* **161**, 431–455 (2003). [https://doi.org/10.1016/S0019-1035\(02\)00043-X](https://doi.org/10.1016/S0019-1035(02)00043-X)
- Z. Tian, H. Chen, B. Fegley, K. Lodders, J.-A. Barrat, J.M.D. Day, K. Wang, Potassium isotopic compositions of howardite-eucrite-diogenite meteorites. *Geochim. Cosmochim. Acta* **266**, 611–632 (2019). <https://doi.org/10.1016/j.gca.2019.08.012>
- V.T. Titov, N.I. Ignatiev, K. McGouldrick, V. Wilquet, C.F. Wilson, Clouds and hazes of Venus. *Space Sci. Rev.* **214**, 126–187 (2018). <https://doi.org/10.1007/s11214-018-0552-z>
- G. Torres, F. Fressin, Discovery of the first Earth-sized planets orbiting a star other than our Sun in the Kepler-20 system (2019). eprint [arXiv:1905.04309](https://arxiv.org/abs/1905.04309)
- A.H. Treiman, Venus - bulk and mantle compositions: are Venus and Earth really twins? in *Venus Geochemistry: Progress, Prospects, and New Missions*. LPI Contribution, vol. 1470

- (2009), pp. 47–48. Abstract number 2016. <https://repository.hou.usra.edu/bitstream/handle/20.500.11753/1177/LPI-001470.pdf?sequence=1>
- J.M. Trigo-Rodríguez, A. Rimola, S. Tanbakouei, V.C. Soto, M. Lee, Accretion of water in carbonaceous chondrites: current evidence and implications for the delivery of water to early Earth. *Space Sci. Rev.* **215**(18), 27 (2019). <https://doi.org/10.1007/s11214-019-0583-0>
- A. Trinquier, J.-L. Birck, C.J. Allegre, Widespread ^{54}Cr heterogeneity in the inner Solar System. *Astrophys. J.* **655**, 1179–1185 (2007). <https://doi.org/10.1086/510360>
- A. Trinquier, J.-L. Birck, C.J. Allegre, C. Gopel, D. Ulfbeck, ^{53}Mn – ^{53}Cr systematics of the early Solar System revisited. *Geochim. Cosmochim. Acta* **72**, 5146–5163 (2008). <https://doi.org/10.1016/j.gca.2008.03.023>
- D.L. Turcotte, An episodic hypothesis for venusian tectonics. *J. Geophys. Res., Planets* **98**, 17061–17068 (1993). <https://doi.org/10.1029/93JE01775>
- A. Udry, G.H. Howarth, C.D.K. Herd, T.J. Lapen, J.M.D. Day, What have meteorites taught us about the Martian interior and surface over the past five years? in *Ninth International Conference on Mars*. LPI Contribution, vol. 2089 (2019). Abstract number 6139. <https://www.hou.usra.edu/meetings/ninthmars2019/pdf/6139.pdf>
- D. Valentian, C. Koppel, P. Mairret, L. Mairret, Venus sample return mission revisited. *ESA Vision 2050 White Paper* (2019). https://www.cosmos.esa.int/documents/1866264/3219248/ValentianD_Venus+sample-return-mission-revisited_r2.pdf/51e80e8b-8ecd-44a9-8363-5525e6cb35d9?t=1565184752220
- E.M.M.E. Van Kooten, D. Wielandt, M. Schiller, K. Nagashima, A. Thomen, K.K. Larsen, M.B. Olsen, Å. Nordlund, A.N. Krot, M. Bizzarro, Isotopic evidence for primordial molecular cloud material in metal-rich carbonaceous chondrites. *Proc. Natl. Acad. Sci.* **113**, 2011–2016 (2016). <https://doi.org/10.1073/pnas.1518183113>
- Venus Science & Technology Definition Team, Venus Flagship Mission Study, NASA (2009) <https://vfm.jpl.nasa.gov/files/Venus+Flagship+Mission+Study+090501-compressed.pdf>
- P. Voosen, Meteorite divide points to Solar System chaos. *Science* **359**, 1451 (2018). <https://doi.org/10.1126/science.359.6383.1451>
- K.J. Walsh, H.F. Levison, Planetesimals to terrestrial planets: collisional evolution amidst a dissipating gas disk. *Icarus* **329**, 88–100 (2019). <https://doi.org/10.1016/j.icarus.2019.03.031>
- K.J. Walsh, A. Morbidelli, S.N. Raymond, D.P. O'Brien, A.M. Mandell, A low mass for Mars from Jupiter's early gas-driven migration. *Nature* **473**, 206–209 (2011). <https://doi.org/10.1038/nature10201>
- K.J. Walsh, A. Morbidelli, S.N. Raymond, D.P. O'Brien, A.M. Mandell, Populating the asteroid belt from two parent source regions due to the migration of giant planets—"The Grand Tack". *Meteorit. Planet. Sci.* **47**(12), 1941–1947 (2012). <https://doi.org/10.1111/j.1945-5100.2012.01418.x>
- K. Wang, S.B. Jacobsen, Potassium isotopic evidence for a high-energy giant impact origin of the Moon. *Nature* **538**, 487–490 (2016). <https://doi.org/10.1038/nature19341>
- P.H. Warren, Stable-isotopic anomalies and the accretionary assemblage of the Earth and Mars: a subordinate role for carbonaceous chondrites. *Earth Planet. Sci. Lett.* **311**, 93–100 (2011). <https://doi.org/10.1016/j.epsl.2011.08.047>
- S. Watanabe, Y. Tsuda, M. Yoshikawa, S. Tanaka, T. Saiki, S. Nakazawa, Hayabusa2 mission overview. *Space Sci. Rev.* **208**, 3–16 (2017). <https://doi.org/10.1007/s11214-017-0377-1>
- M.J. Way, A.D. Del Genio, N.Y. Kiang, L.E. Sohl, D.H. Grinspoon, I. Aleinov, M. Kelley, T. Clune, Was Venus the first habitable world of our Solar System? *Geophys. Res. Lett.* **43**, 18376–8383 (2016). <https://doi.org/10.1002/2016GL069790>
- C.R. Webster, P.R. Mahaffy, G.J. Flesch, P.B. Niles, J.H. Jones, L.A. Leshin, S.K. Atreya, J.C. Stern, L.E. Christensen, T. Owen, H. Franz, R.O. Pepin, A. Steele (The MSL Science Team), Isotope ratios of H, C, and O in CO₂ and H₂O of the Martian atmosphere. *Science* **341**, 260–263 (2013). <https://doi.org/10.1126/science.1237961>
- S.J. Weidenschilling, Accretion of the asteroids: implications for their thermal evolution. *Meteorit. Planet. Sci.* **54**, 1115–1132 (2019). <https://doi.org/10.1111/maps.13270>
- M.K. Weisberg, T.J. McCoy, A.N. Krot, in *Systematics and Evaluation of Meteorite Classification. Meteorites and the Early Solar System II*. D.S. Lauretta, H.Y. McSween Jr. (University of Arizona Press, Tucson, 2006), pp. 19–52. https://repository.si.edu/bitstream/handle/10088/20577/min_Weisberg_et_al_2006_In_Meteorites_and_the_Early_Solar_System_II_Univ_of_Arizona_Press_19-52.pdf
- L.C. Welzenbach, M.D. Fries, M.M. Grady, R.C. Greenwood, F.M. McCubbin, C.L. Smith, A. Steele, R.A. Zeigler, Potential alteration products of organic materials by X-ray computed tomography of Mars returned samples, in *82nd Annual Meeting of the Meteoritical Society*. LPI Contribution, vol. 2157 (2019). Abstract number 6369. <https://www.hou.usra.edu/meetings/metsoc2019/pdf/6369.pdf>
- G. Whitcomb, J. Lebreton, G. Scoon, Venus sample return mission, in *34th COSPAR Scientific Assembly, the Second World Space Congress* (2002). Abstract 1891. <https://ui.adsabs.harvard.edu/abs/2002cosp...34E1891W/abstract>

- J.L. Whitten, B.A. Campbell, Variations in the radar properties of tesserae across Venus as observed with Magellan data, in *50th Lunar and Planetary Science Conference*. LPI Contribution, vol. 2132 (2019). Abstract 2558. <https://www.hou.usra.edu/meetings/lpsc2019/pdf/2558.pdf>
- U. Wiechert, A.N. Halliday, D.-C. Lee, G.A. Snyder, L.A. Taylor, D. Rumble, Oxygen isotopes and the Moon-forming giant impact. *Science* **294**, 345–348 (2001). <https://doi.org/10.1126/science.1063037>
- D.R. Williams, Venus Fact Sheet. NASA Goddard Space Flight Centre online resource, updated September 2018 (2018a). <https://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html>
- D.R. Williams, Mars Fact Sheet. NASA Goddard Space Flight Centre online resource, updated September 2018 (2018b). <https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html>
- D.R. Williams, Planetary Fact Sheet, NASA Goddard Space Flight Centre online resource, updated October 2019 (2019a). <https://nssdc.gsfc.nasa.gov/planetary/factsheet/>
- D.R. Williams, Asteroid Fact Sheet. NASA Goddard Space Flight Centre online resource, updated September 2019 (2019b). <https://nssdc.gsfc.nasa.gov/planetary/factsheet/asteroidfact.html>
- D.R. Williams, Chronology of Venus Exploration, NASA Goddard Space Flight Centre online resource, updated February 2020 (2020a). https://nssdc.gsfc.nasa.gov/planetary/chronology_venus.html
- D.R. Williams, Chronology of Mars exploration, Exploration, NASA Goddard Space Flight Centre online resource, updated February 2020 (2020a). https://nssdc.gsfc.nasa.gov/planetary/chronology_mars.html
- C.F. Wilson et al., Venus: Key to understanding the evolution of terrestrial planets (2019). <https://ui.adsabs.harvard.edu/#abs/2019arXiv190804269W/abstract>
- E.T. Wolf, O.B. Toon, Delayed onset of runaway and moist greenhouse climates for Earth. *Geophys. Res. Lett.* **41**(1), 167–172 (2014). <https://doi.org/10.1002/2013GL058376>
- A.N. Youdin, J. Goodman, Streaming instabilities in protoplanetary discs. *Astrophys. J.* **620**, 459–469 (2005). <https://doi.org/10.1086/426895>
- E.D. Young, S.S. Russell, Oxygen reservoirs in the early solar nebula inferred from an Allende CAI. *Science* **282**, 452–455 (1998). <https://doi.org/10.1126/science.282.5388.452>
- E.D. Young, I.E. Kohl, I.P.H. Warren, D.C. Rubie, S.A. Jacobson, A. Morbidelli, Oxygen isotopic evidence for vigorous mixing during the Moon-forming giant impact. *Science* **351**, 493–496 (2016). <https://doi.org/10.1126/science.aad0525>
- H. Yurimoto, K. Kuramoto, Molecular cloud origin for the oxygen isotope heterogeneity in the Solar System. *Science* **305**, 1763–1766 (2004). <https://doi.org/10.1126/science.1100989>
- H. Yurimoto, K. Kuramoto, A.N. Krot, E.R.D. Scott, J.N. Cuzzi, M.H. Thieme, J.R. Lyons, Origin and evolution of oxygen isotopic compositions of the Solar System, in *Protostars and Planets*, vol. 951, ed. by V.V.B. Reipurth, D. Jewitt, K. Keil (University of Arizona Press, Tucson, 2007), pp. 849–862. <https://www.lpi.usra.edu/books/PPV/8057.pdf>
- C.Z. Zhang, K. Zhang, On the internal structure and magnetic fields of Venus. *Earth Moon Planets* **69**, 237–247 (1995). <https://doi.org/10.1007/BF00643786>