Published in final edited form as:
Earth Space Sci. 2019 June 25; 6(7): 1299–1318. doi:10.1029/2018EA000536.

Venus Atmospheric Composition *in situ* Data: A Compilation

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Abstract

The Venus atmosphere is of significant interest yet only rudimentary solid data has been gathered about its composition and chemistry. These measurements are scattered through time and place and are limited by parameters such as resolution and error margins as well as reinterpretations. This paper presents an extensive compilation of published *in situ* data for the atmospheric composition of Venus. It also includes remotely gathered measurements and some extrapolated and modeled data for the lower atmosphere. The composition tables are divided in four categories: noble gases, reactive gases, noble and non-noble isotopes. These tables were first presented in 2016 within the scientific heritage appendix of the Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission proposal. These tables provide respective measurements, error margins, techniques, altitudes, instruments, mission and references. The objective of this paper is to provide a simple, comprehensive list of available measurements to date; in particular, the *in situ* data, to serve as a quick overall Venus atmosphere data reference.

Key point / Plain language summary:

A compilation of *in situ* Venus atmospheric data from a variety of journals and difficult to locate sources.

Keywords

Venus; atmosphere; noble gases; reactive gases; isotopes; in situ data

1. Introduction

Venus is our nearest planetary neighbor, excluding the Moon, yet we only have rudimentary knowledge of its deep atmosphere and geology. This is not for the lack of trying. Several spacecraft have been sent to Venus, either as orbiters, atmospheric probes, or landers, with differing levels of success. There have been opportunistic observations of Venus using instruments on spacecraft 'flybys' that were headed elsewhere as well as numerous Venus observations conducted from Earth-based telescopes or made with the naked-eye. The motivation for this paper was to create an easily accessible manuscript that contains the sum total of all previous measured and modeled Venus composition data that could be used as a

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straightforward reference. Specifically, the renewed interest in sending spacecraft to Venus, as demonstrated by the recent NASA Discovery and New Frontiers Mission opportunities, justified such a compilation. In the early stages, it appeared that this task would be both simple and quick but it became quickly evident that without proper guidelines, this effort would devolve into a multifaceted morass. Therefore, we compiled an extensive list of published *in situ* measurements of the Venus atmosphere with some additional data derived from modeling.

The Venus environment is characterized by extreme conditions from the global sulfuric acid clouds to the high temperatures and pressures present at the surface (740 K and 95.6 bar). This challenging environment resulted in relatively few *in situ* measurements and remote observations are for the most part, limited to the region above the clouds. This dearth of hard data restricts what can be ascertained directly and requires the use of models in order to predict complex composition and processes within the Venus atmosphere. As a result, it is not uncommon for some extrapolated/modeled data to be quoted as ‘fact’, particularly for the deep atmosphere (below the clouds to the surface). There exist a large variety of Venus data compilations and presentations but an inescapable fact is that the *in situ* compositional data of the deep atmosphere, originates from the Venera, VeGa and Pioneer Venus missions. The last of these missions, VeGa 2, completed its task in June 1985. It should be noted that none of the entry/descending probes of the Venera or Pioneer missions were able to collect composition data until the probes became sub-sonic which typically occurred below 64km in almost all of the cases. More recent data was obtained through remote Earth-based, fly-by or orbiter observations. Tables 1a and 1b lists the spacecraft and Earth/space-based facilities that have gathered data about Venus and whose data is reflected in this compilation.

1.1 Overview of Previous Venus Atmospheric Data Compilation Studies

The Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission proposal included a science heritage table within its appendix on the atmospheric composition of Venus. While conducting background research for this mission, it was evident that there needed to be one comprehensive, clear-cut table of the existing measured Venus atmospheric data. Limaye *et al.* (2018) present a comprehensive review of Venus thermal structure and radiative balance results but not the composition. Some previous compilations, although unquestionably excellent such as the Venus International Reference Atmosphere, aka VIRA, (Kliore *et al.* 1985), are now outdated while others were unclear or did not explain how values were derived. Imagine the frustration when significant literature digging was required to determine whether a value was an extrapolation, or has been accepted as ‘fact’ because the original source receded far into citation history, or had been derived solely from models or from well-studied estimates. This additional research was, unsurprisingly, neither straightforward nor swift due to difficulty in obtaining original sources, if cited at all. It was also easy to fall into a false sense of knowledge regarding the breadth of data because, at first, the data appear comprehensive but upon closer inspection, the data is limited in scope either by vertical resolution, massive error bars, or having no measurements whatsoever, *i.e.*, oxygen at depth. This paper includes the aforementioned Venus data compilation from the DAVINCI proposal and recently obtained remote data. It is hoped that this presentation of the current knowledge of Venus’ atmospheric composition data will save future investigators the frustration and effort of tracking down the proverbial needles in a haystack. The intent is to not to debate whether a measurement or estimate was made correctly or not; rather it is to report in one place currently known and published measurements regarding the Venus atmosphere.

2. Methodology

2.1 Measurement Discussion

The data in these tables list measured values and a concerted effort was made to only include data from original sources. Modeled data were mostly avoided, unless well justified, in order to maintain the basic original data integrity of the tables. As such, the values presented in this paper are taken verbatim from the sources using original units and connotations unless noted otherwise. Later papers that quote the same value from an earlier source are not included. Some values that were tweaked over the years are also included if the reworked values have clear explanations and techniques. In order to ease access and understanding, the tables include a comment column for each item to provide information that is not reflected is the main body of the table. For example, a statement about how the data value was derived or settled upon would be noted from the original source. Theoretical or modelled data are indicated.

While compiling this data and speaking with researchers in the community, it became apparent that is not always obvious how the measurements are reported. The terms abundance and 'mole fraction' have been used interchangeably which, at times, has led to confusion as to what exactly the measurements represent. As this situation appears to occur fairly often, it seemed to be a useful exercise to clarify the measurement definition with a brief overview. When we refer to one of the first major and commonly cited compendiums of measured data, von Zahn *et al.* (1983), the reported measurements for each species are provided as mixing ratios: "We provide … mixing ratios $x_i = n_i/\Sigma\ n_i$, (with n_i being the number density of species i) of all those gases which have been positively identified in Venus's atmosphere below 100 km." The number density is a fixed number of particles (or molecules) for a given volume not to be confused with number fraction, which is defined as the number of molecules of a species n_i divided by the total number of all molecules n_{total}. Confusion creeps in when the term abundance appears because this term is not precise and requires context as to whether the value refers to the total amount of a species or as a comparison ratio to the whole. Additionally, measured values are also reported as ppmv (parts per million by volume) and should not be confused with concentration. The 'v' in this context (ppmv or ppm_v) refers to the volume mixing ratio to differentiate it from other types of mixing ratios *(e.g.* Schwartz and Warneck, 1995). The purpose of describing these minutiae is to illustrate how easily confusion could occur. Fortunately, we are dealing with gases which allows straightforward calculations to compare measurements. In atmospheric chemistry, the mixing ratio usually refers to the mole ratio (r_i) as shown in Eq. 1 where N_i is the number of moles of species i such that $N_i = n_i/Avogadro's\ number$.

$$r_i = \frac{N_i}{N_{total} - N_i} \qquad (1)$$

The mole fraction, x_i, is defined in Eq. 2 as:

$$x_i = \frac{N_i}{\sum_{i=1}^{k} N_i} = \frac{N_i}{N_{total}} \tag{2}$$

If $N_i \ll N_{total}$, then r_i is almost identical ($r_i \approx x_i$) to the mole fraction, x_i. This is particularly true if N_i is small which is the case on Venus where CO_2 and N_2 dominate the atmosphere at fractions of ~96.5% and ~3.5%, respectively. Therefore, the mixing ratio on Venus is essentially the mole fraction and represents the same quantity.

For the purposes of this compilation all measurements, unless noted otherwise, are stated as mole fractions for the reasons just described.

2.2 Measurement Errors

The errors shown within the tables reflect what was noted in the original sources. Unfortunately, many sources do not specify the error ranges, whether the error was 1 or 3 sigma or if the error came about due to instrumental bias.

3. Data Tables

3.1 Noble Gases: Table 2

3.2 Noble Gas Isotopes and Associated Isotopic Ratios: Table 3

3.3 Reactive Gases: Table 4

3.4 Isotopic Ratios of the Reactive Gases: Table 5

4. Summary

These Tables are by no means the last word on Venus atmospheric data, both measured and modelled, but rather provide a useful overall reference for future work. We look forward to obtaining new information about Venus' atmosphere from the cloud-tops to the surface and the exciting, new missions that hopefully, will eventually and inevitably be sent to Venus.

Acknowledgements:

Many thanks are extended to those who preceded this work. Apologies are given to Venus modelers whose work is not included. This compilation would not have come to pass without the encouragement and support of the DAVINCI Principle Investigator Dr. Lori Glaze, the DAVINCI Team, and the Astrochemistry Lab Branch/691 at Goddard Space Flight Center. The reviewers were instrumental in clarifying the discussion and provided valuable insight. All the data presented within this manuscript are accessible in the published literature through the cited references.

References:

Baines KH, Atreya SK, Bullock MA, Grinspoon DH, Mahaffy P, Russell CT, Schubert G, & Zahnle K (2013). The atmospheres of the terrestrial planets: Clues to the origins and early evolution of Venus, Earth, and Mars In Mackwell S, Simon-Miller A, Harder JW, and Bullock M (Eds.), Climatology of Terrestrial Planets (pp. 137–160). Tucson, AZ: Univ. Arizona Press.

Bertaux J-L, Widemann T, Hauchecorne A, Moroz VI, & Ekonomov AP (1996), VEGA 1 and VEGA 2 entry probes: An investigation of local UV absorption (220–400 nm) in the atmosphere of Venus (SO_2, aerosols, cloud structure). Journal of Geophysical Research, 101(E5), 12,709–12,746.

Bertaux J-L, 18 coauthors & the SPICAV/SOIR team (2007), A warm layer in Venus' cryosphere and high-altitude measurements of HF, HCl, H_2O and HDO. Nature, 450(7170), 646–649. [PubMed: 18046397]

Bézard B, de Bergh C, Fegley B, Maillard J-P, Crisp D, Owen T, Pollack JP, & Grinspoon D (1993), The abundance of sulfur dioxide below the clouds of Venus, Geophysical Research Letters, 20, 1587–1590.

Bézard B (1994), The deep atmosphere of Venus probed by near-infrared spectroscopy of the night side. Communication at the 30th COSPAR Scientific Assembly (Session C3.1), 11–21 July, Hamburg, Germany Cited in Taylor et al in Venus II.

Bézard B, Baluteau JP, Marten A, & Coron N (1987), The $^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratios in the atmosphere of Venus From high-resolution 10-micron spectroscopy. Icarus 72(3),623–34.

Bézard B, DeBergh C, Crisp D, & Maillard JP (1990), The deep atmosphere of Venus revealed by high-resolution nightside spectra. Nature, 345, 508–11.

Connes P, Connes J, Benedict WS, & Kaplan LD (1967), Traces of HCl and HF in the atmosphere of Venus, Astrophysical Journal, 147, 1230–1237.

Connes P, Connes J, Kaplan LD, & Benedict WS (1968), Carbon monoxide in the Venus atmosphere, Astrophysical Journal, 152, 731–743

de Bergh C, Bezard B, Crisp D, Maillard J-P, Owen T, Pollack J, & Grinspoon D (1995), Water in the deep atmosphere of Venus from high-resolution spectra of the nightside, Advances in Space Research, 15(4), 79–88.

de Bergh C, Bezard B, Owen T, Crisp D, Maillard J-P, & Lutz BL (1991), Deuterium on Venus: Observations from Earth, Science, 251(4993), 547–549. [PubMed: 11538265]

de Bergh C, Maillard J-P, Bezard B, Owen T, & Lutz BL (1989), Ground-based high resolution spectroscopy of Venus near 3.6 microns, Bulletin of the American Astronomical Society, 21: 926.

Donahue TM (1986,. Fractionation of noble gases by thermal escape from accreting planetesimals, Icarus, 66(2), 195–210.

Donahue TM & Hodges RR (1993), Venus methane and water, Geophysical Research Letters, 20, 591–594.

Donahue TM, Hoffman JH, & Hodges RR (1981), Krypton and xenon in the atmosphere of Venus, Geophysical Research Letters, 8, 513–516.

Donahue TM, Hoffman JH, Hodges RR, & Watson AJ (1982), Venus was wet: A measurement of the ratio of deuterium to hydrogen, Science, 216(4546), 630–33. [PubMed: 17783310]

Esposito LW (1981), Absorber seen near the Venus cloud tops from Pioneer Venus, Advances in Space Research, 1, 163–166. [PubMed: 11541706]

Gel'man BG, Zolotukhin VG, Lamonov NI, Levchuk BV, Mukhin LM, Nenarokov DF, et al. (1979a), An analysis of the chemical composition of the atmosphere of Venus on an AMS of the Venera-12 using a gas chromatograph, Kosmich. Issled 17:708 Cosmic Research, 17:585 (11pps).

Gel'man BG, Zolotukhin VG, Lamonov NI, Levchuk BV, Mukhin LM, Nenarokov DF, et al. (1979b), Venera 12 analysis of Venus atmospheric composition by gas chromatography, Pisma v Astronomicheskii Zhurnal, 5, 217–21.

Hoffman JH, Hodges RR, Donahue TM, & McElroy MB (1980a), Composition of the Venus lower atmosphere from the Pioneer Venus mass spectrometer, Journal of Geophysical Research, 85(13), 7882–90.

Hoffman JH, Hodges RR, Donahue TM, McElroy MB, & Koplin M (1979), Composition and structure of the Venus atmosphere: Results from Pioneer Venus, Science, 205, 49–52. [PubMed: 17778898]

Hoffman JH, Hodges RR, Wright WW, Blevins VA, Duerksen KD, & Brooks LD (1980b), Pioneer Venus sounder probe neutral gas mass spectrometer, IEEE Transactions on Geoscience and Remote Sensing, 18(1), 80–84.

Ignatiev NI, Moroz VI, Moshkin BE, Ekonomov AP, Gnedykh VI, Grigoriev AV, & Khatuntsev IV (1997), Water vapour in the lower atmosphere of Venus: A new analysis of optical spectra measured by entry probes, Planetary and Space Science, 45(4), 427–438.

Istomin VG, Grechnev KV, & Kotchnev VA (1980a), Mass spectrometer measurements of the composition of the lower atmosphere of Venus, Space Research-COSPAR Colloquia Series, 20, 215–218.

Istomin VG, Grechnev KV & Kotchnev VA (1980b), Mass spectrometry of the lower atmosphere of Venus: Krypton isotopes and other results of the Venera-11 and −12 data processing. "23rd COSPAR meeting" held in Budapest, Hungary preprint D-298, Space Res. Inst., Acad of Science USSR.

Jenkins JM, Kolodner MA, Butler BJ, Suleiman SH, & Steffes PG (2002), Microwave remote sensing of the temperature and distribution of sulfur compounds in the lower atmosphere of Venus, Icarus, 158, 312–28. doi:10.1006/icar.2002.6894

Krasnopolsky VA & Gladstone GR (2005), Helium on Mars and Venus: EUVE observations and modeling, Icarus, 176, 395–407.

Kliore AJ, Moroz VI & Keating GM (1985), The Venus International Reference Atmosphere. Adv. Space Res. 5 (11), pp. viii+305, A. J. Kliore, V. I. Moroz, & G. M. Keating (Editors) ISBN 0-08-034631-6.

Kumar S & Hunten DM (1974), Venus: An ionospheric model with an exospheric temperature of 350 K, Journal of Geophysical Research, 79, 2529–2532.

Limaye SS, Grassi D, Mahieux A, Migliorini A, Tellmann S, & Titov D (2018) Venus Atmospheric Thermal Structure and Radiative Balance. Space Science Reviews, 214:102 10.1007/s11214-018-0525-2

Lodders K & Fegley B Jr, (1998). The Planetary Scientists Companion. New York: Oxford Press, p. 120.

Marcq E, Bezard B, Drossart P, Piccioni G, Reess JM, and Henry F (2008). A latitudinal survey of CO, OCS, H_2O, and SO_2 in the lower atmosphere of Venus: Spectroscopic studies using VIRTIS-H. Journal of Geophysical Research, 113, E00B07.

Marov MY, Volkov VP, Surkov YA, & Ryvkin ML (1989). The lower atmosphere In Barsukov VL and Volkov VP (Eds.), The planet Venus: atmosphere, surface, interior structure (pp. 25–67). Moscow, USSR: Nauka In Russian.

Mauersberger K, von Zahn U & Krankowsky D (1979), Upper limits on argon isotope abundances in the Venus thermosphere, Geophysical Research Letters, 6(8), 671–74.

Moroz VI, Parfent'ev NA, & Sanko NF (1979), Spectrophotometric experiment on the Venera 11 and Venera 12 descent modules. 2. Analysis of Venera 11 spectra data by the layer-addition method, Cosmic Research, 17, 601–614.

Moroz VI, Golovin YM, Ekonomov AP, Moshkin BE, et al. 1980, Nature 284, 243–244 (orig cited in LF1998)

Mukhin LM, et al. (1983), Gas chromatograph analysis of the chemical composition of the atmosphere of Venus by the landers of the Venera 13 and Venera 14 spacecraft, Cosmic. Research, 21, 168–172.

Na CY, Esposito LW, & Skinner TE (1990), International ultraviolet explorer observations of Venus SO_2 and SO, Journal of Geophysical Research, 95, 7485–7491.

Oyama KI, Carle GC, Woeller JB, Pollack JB, Reynolds RT, & Craig RA (1980), Pioneer Venus gas chromatography of the lower atmosphere of Venus, Journal of Geophysical Research, 85(13), 7891–7902.

Pepin RO (1991), On the origin and early evolution of terrestrial planet atmospheres and meteoritic volatiles, Icarus, 92(1), 2–79.

Peplowski PN & Lawrence DJ (2016), Nitrogen content of Venus' upper atmosphere from the MESSENGER neutron spectrometer, 47th Lunar & Planetary Science Conference, Abstract# 1177.

Pollack JB, Dalton JB, Grinspoon D, Wattson RB, Freedman R et al. (1993), Near-infrared light from Venus' nightside: A spectroscopic analysis, Icarus, 103, 1–42.

Schwartz SE & Warneck P (1995), Units for use in atmospheric chemistry, Pure and Applied Chemistry, 67(8/9), 1377–1406.

Siddiqi AA (2002). Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes 1958–2000 Monographs in Aerospace History, Number 24, NASA/SP-2002–4524.

Taylor FW, Crisp D, & Bezard B (1997). Near-infrared sounding of the lower atmosphere of Venus In Bougher SW, Hunten DM, and Phillips R (Eds.), Venus II (pp. 325–351). Tucson, AZ: Univ. Arizona Press.

Tsang CCC, Taylor FW, Wilson CF, Liddell SJ, Irwin PGJ, Piccioni G, Drossart P, and Calcutt SB (2009), Variability of CO concentrations in the Venus troposphere from Venus Express/VIRTIS using a Band Ratio Technique, Icarus, 201, 432–443.

von Zahn U, Fricke KH, Hunten DM, Krankowsky D, Mauersberger K, & Nier OA (1980), The upper atmosphere of Venus during morning conditions, Journal of Geophysical Research, 85(A13), 7,829–7,840.

Winick JR & Stewart AIF (1980), Photochemistry of SO_2 in Venus' upper cloud layers, Journal of Geophysical Research, 85,7849–7860.

Young LDG (1972). High-resolution spectra of Venus: A review, Icarus, 17, 632–658.

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Table 1a:

Missions to Venus and Spacecraft that returned Venus data

Date Launched	Name (Nation)[a]	Type	Venus Date[b] (Lat, Long)	Comments
27 Aug 1962	Mariner 2 (USA)	Flyby	14 Dec 1962 *(n/a)*	First successful Venus flyby
12 Jun 1967	Venera 4 (USSR)	Probe	18 Oct 1967 (unknown)	First spacecraft to transmit data from a planet's atmosphere
14 Jun 1967	Mariner 5 (USA)	Flyby	19 Oct 1967 *(n/a)*	
5 Jan 1969	Venera 5 (USSR)	Probe	16 May 1969 (3°S, 18°)	
10 Jan 1969	Venera 6 (USSR)	Probe	17 May 1969 (5°S, 23°)	
17 Aug 1970	Venera 7 (USSR)	Lander	15 Dec 1970 (5°S, 351°)	First transmissions from the surface of another planet
27 Mar 1972	Venera 8 (USSR)	Lander	22 Jul 1972 (10°S, 335°)	
3 Nov 1973	Mariner 10 (USA)	Flyby	5 Feb 1974 *(n/a)*	
8 Jun 1975	Venera 9 (USSR)	Orbiter/Lander	22 Oct 1975 (32°N, 291°)	First image of Venus surface
14 Jun 1975	Venera 10 (USSR)	Orbiter/Lander	25 Oct 1975 (16°N, 291°)	Transmitted 65min from surface; Surface images
20 May 1978	Pioneer Venus 1 (USA)	Orbiter	4 Dec 1978 *(n/a)*	Radar map 73°N/63°S @ 75km resolution; in operation for ~14yrs
8 Aug 1978	Pioneer Venus 2 (USA)	Multiprobe 1 large 3 small	9 Dec 1978 (4.4°N, 304°; Large Probe)	Small probes: North (59.3°N,4.8°); Day (31.3°S,317°); Night (28.7°S,56.7°) Two of three survived impact
9 Sep 1978	Venera 11 (USSR)	Flyby/Lander	25 Dec 1978 (14°S, 299°)	Date reflects surface landing
14 Sep 1978	Venera 12 (USSR)	Flyby/Lander	21 Dec 1978 (7°S, 294°)	Lander relayed data for 110 minutes after reaching the surface.
30 Oct 1981	Venera 13 (USSR)	Flyby/Lander	1 Mar 1982 (7.5°S, 305°)	First color images of Venus surface; relayed data for 127 mins
4 Nov 1981	Venera 14 (USSR)	Flyby/Lander	5 Mar 1982 (13.25°S, 310°)	Lander relayed data for 57 minutes after reaching the surface.
2 Jun 1983	Venera 15 (USSR)	Orbiter	10 Oct 1983 *(n/a)*	Mapping
7 Jun 1983	Venera 16 (USSR)	Orbiter	14 Oct 1983 *(n/a)*	Mapping
15 Dec 1984	VeGa 1 (USSR)	Flyby/Probe/ Lander	11 Jun 1985 (7.2°N, 177.8°)	Balloon-gondola gathered atmos data (survived 46.5 hrs); lander relayed data for 56 mins
21 Dec 1984	VeGa 2 (USSR)	Flyby/Probe/ Lander	15 Jun 1985 (6.45°S, 181.08°)	Balloon-gondola gathered atmos data (survived 46.5 hrs); lander relayed data for 57 mins
4 May 1989	Magellan (USA)	Orbiter	10 Aug 1990 *(n/a)*	Radar mapping; 98% coverage; remained in orbit ~4 yrs
4 Aug 2004	MESSENGER (USA)	Flyby	24 Oct 2006 5 Jun 2007 *(n/a)*	Destination: Mercury Remote measurements/images of Venus atmosphere
9 Nov 2005	Venus Express (Europe)	Orbiter	7 May 2006 *(n/a)*	Global mapping; remote analyses; plasma, cloud, atmos studies; final mission duration ~9 yrs
20 May 2010	Akatsuki (Japan)	Orbiter	7 Dec 2015 *(n/a)*	Failed initial orbit 2010 insertion; atmos dynamics & cloud physics; ongoing

[a]Mission design and operation: NASA(USA), Lavochkin(USSR), ESA(Europe), JAXA(Japan)

[b]Date of flyby/entry/landing of spacecraft; if known, Venus latitude and longitude of final resting spot.

Table 1b:

Earth- and Space-based facilities referenced in this study for Venus data

Facility/Spacecraft	Instrument	Comments
Apache Point Observatory	3.5 m Telescope	TripleSpec spectrograph
Extreme Ultraviolet Explorer (EUVE)	Wolter-Schwarzschild Type II grazing incidence mirror	Launch: June 1992 Deactivated: Jan 2001
Mauna Kea Observatories	Canada-France-Hawaii 3.6m Telescope	Fourier Transform Spectrometer
International Ultraviolet Explorer (IUE)	Long Wavelength Primary Camera: High Dispersion Mode/Small Aperture	Launch: Jan 1978 Decommission:Sept 1996
NRAO Very Large Array	Radio observations	Microwave frequencies
Observatoire de Haute Provence, France	1.9 m Telescope	Michelson Interferometer

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Table 2:

Noble gases

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
He	12 ppm	+24, −8 ppm	< 100 km	Extrapolation	mass spectrometer PV-BNMS (bus) PV-ONMS (orbiter)	Pioneer Venus	Extrapolated from measurements taken above 130km	von Zahn *et al.* 1983: pp. 325, 406–407 Tables II & XI
He	9 ppm	± 6 ppm	middle to lower atmosphere	Extrapolation	UV spectroscopy	EUVE	Measured He 584 Å, calculated brightness as function of He mixing ratio using radiative transfer code. Extrapolate to lower atmosphere. Error accounts for uncertainty in eddy diffusion.	Krasnopolsky and Gladstone 2005: p. 399
Ne	7 ppm	± 3 ppm	< 100 km	Compiled *in situ* data	mass spectrometers	Venera 11/12 Pioneer Venus	• von Zahn recommended mean value • Combination of 3 adopted values (corrected/normalized)	von Zahn *et al.* 1983: pp. 325, 408–409 Tables II & XII
Ne	10 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a; pp. 7886–7887, Table 2
Ne	12 ppm	+5, −3 ppm	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	• Value reflects ^{20}Ne mixing ratio • relative to measured Ar	Istomin *et al.* 1980b: p. 16
Ne	< 8 ppm	-	51.6 km	*in situ*	LGC	Pioneer Venus	Sum of all neon peaks	Oyama *et al.* 1980; p. 7897, Table 2
Ne	10.6 ppm	+31.6–9.6 ppm (3σ) ± 3.7 ppm (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus	Sum of all neon peaks	Oyama *et al.* 1980; p. 7897, Table 2
Ne	4.31 ppm	+5.54–3.91 ppm (3σ) ± 0.65 ppm (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus	Sum of all neon peaks	Oyama *et al.* 1980; p. 7897, Table 2
Ar	70 ppm	± 25 ppm	< 100 km	Compiled *in situ* data	mass spectrometers gas chromatograph	Pioneer Venus Venera 11/12	• von Zahn recommended mean value • Combination of reported values (corrected/normalized) • Referenced to ^{36}Ar	von Zahn *et al.* 1983: pp. 325, 409–410 Tables II & XIII

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
Ar	70 ppm	+50, −30 ppm	< 25 km	*in situ*	LNMS	Pioneer Venus	• Sum of three Ar isotopes; see Hoffman Ar isotope data below	Hoffman *et al.* 1980b: pp. 7876, Table 2
Ar	100 ppm	-	26 km to surface	*in situ*	mass spectrometers	Venera 13/14	• Sum of ^{36}Ar, ^{38}Ar, and ^{40}Ar	Istomin *et al.* 1982: p. 214, Table III
Ar	110 ppm	± 20 ppm	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	• Sum of ^{36}Ar, ^{38}Ar, and ^{40}Ar • Expected sensitivity 1 ppm	Istomin *et al.* 1980b: p. 15
Ar	150 ppm	± 50 ppm	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	• Sum of three Ar isotopes • Expected sensitivity 1 ppm • Value superceded by Istomin *et al* 1980b.	Istomin *et al* 1980a: p. 217, Table 1
Ar	60.5 ppm	+39.5–46.8 ppm (3σ) ± 5.5 ppm (1σ)	51.6 km	*in situ*	LGC	Pioneer Venus	Value sums Ar isotopes	Oyama *et al.* 1980: p. 7897, Table 2
Ar	63.8 ppm	± 13.6 ppm (3σ) ± 1.6 ppm (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus	Value sums Ar isotopes	Oyama *et al.* 1980: p. 7897, Table 2
Ar	67.2 ppm	± 2.3 ppm (3σ) ± 0.3 ppm (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus	Value sums Ar isotopes	Oyama *et al.* 1980: p. 7897, Table 2
Ar	40 ppm	± 20 ppm	< 42 km	*in situ*	gas chromatograph	Venera 12	• Eight atmospheric samples • Results presented as(4±2) × 10^{-3} %	Gel'man *et al.* 1979: Table 1
Kr	0.05 ppm	± 0.025 ppm	< 100 km	Compiled *in situ* data	LNMS	Pioneer Venus	• No clear choice between the two Kr data measurements; discussed in von Zahn reference • Note ^{84}Kr values	von Zahn *et al.* 1983: pp. 410–412 Tables II & XIV
	0.7 ppm	± 0.35 ppm	< 100 km	Compiled *in situ* data	mass spectrometers	Venera 11/12		
Kr	47 ppb	+22, −35 ppb	< 30 km	*in situ*	LMNS	Pioneer Venus	• Sum of $^{80-84}$Kr • Upper limit 69 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: pp. 514–515 Donahue and Pollack 1983: Table I
Xe	< 40 ppb	-	< 30 km	*in situ* derived	LNMS	Pioneer Venus	• Sum of $^{128-132}$Xe • Upper limit 120 ppb	Donahue *et al* 1981: pp. 513–514

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Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
							• Values derived from data gathered and influenced by conflicting results on krypton	

[a] Acronyms: BNMS - Bus Neutral Mass Spectrometer; ONMS - Orbiter Neutral Mass Spectrometer; LNMS – Large probe Neutral Mass Spectrometer; LGC - Large probe Gas Chromatograph

Table 3:

Noble gas isotopes and associated isotopic ratios

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
^{3}He/^{4}He	< 3 × 10^{-4}	-	< 24 km	*in situ*	LNMS	Pioneer Venus	• Upper limit value; see discussion in references • *Calculated from ratio: ^{3}He ≈ 3.6 ppb*	Hoffman *et al.* 1980a; p. 7887, Table 3 von Zahn *et al.* 1983: p. 426, Table XVI
^{20}Ne	9 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a; p. 7887, Table 2
^{20}Ne	10 – 15 ppm	-	23 to 1.5 km	*in situ*	mass spectrometers	Venera 11/12	Expected instrument sensitivity 5 ppm	Istomin *et al.* 1980a: p. 217
^{20}Ne	~10 ppm	-	26 km to surface	*in situ*	mass spectrometers	Venera 13/14		Istomin *et al.* 1982: p. 213
^{22}Ne	1 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a; p. 7887, Table 2
^{22}Ne/^{20}Ne	0.07	± 0.02 (1σ)	~62 km	*in situ*	LNMS	Pioneer Venus	Measured in enriched noble gas sample via the isotope ratio measurement cell (IRMC)	Hoffman *et al.* 1980a; p. 7887, Table 3
^{20}Ne/^{22}Ne	11.8	± 0.7	< 25 km	*in situ*	mass spectrometer	Pioneer Venus		Donahue 1986: p. 196
^{20}Ne/^{22}Ne	11.9	± 0.7 (1σ)	26 km to surface	*in situ*	mass spectrometer	Venera 13	1st *in situ* cycle of Venus 13 MX-6411	Istomin *et al.* 1982: p. 213, Table II
^{20}Ne/^{22}Ne	11.7	± 0.7 (1σ)	26 km to surface	*in situ*	mass spectrometer	Venera 13	3rd *in situ* cycle of Venus 13 MX-6411	Istomin *et al.* 1982: p. 213, Table II
^{20}Ne/^{36}Ar	0.3	± 0.2	< 24 km	*in situ*	LNMS	Pioneer Venus		Hoffman *et al.* 1980a; p. 7887, Table 3
^{21}Ne/^{22}Ne	< 0.067	-	< 100 km	theory			Noted as common planet origin hypothesis	Baines *et al* 2013: p. 146, Table 1
^{22}Ne/^{21}Ne	< 10	-	26 km to surface	*in situ*	mass spectrometers	Venera 13/14	Estimate based on raw telemetry	Istomin *et al.* 1982: p. 214
^{21}Ne/^{22}Ne	< 0.06	-	< 100 km	theory				Donahue 1986: p. 196
^{36}Ar	13 ppm	-	~ 135 km	*in situ*	mass spectrometer PV-BNMS	Pioneer Venus	• Upper limit • Relative to CO_2	Mauersberger *et al.* 1979: p. 672
^{40}Ar	28 ppm	-	~ 135 km	*in situ*	mass spectrometer PV-BNMS	Pioneer Venus	• Upper limit	Mauersberger *et al.* 1979: p. 672

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Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
							• Relative to CO_2	
^{36}Ar	< 9 ppm	-	< 100 km	extrapolation	mass spectrometer PV-BNMS	Pioneer Venus	• Upper limit; see 135km data • Relative to CO_2	Mauersberger *et al.* 1979: p. 673
^{40}Ar	< 20 ppm	-	< 100 km	extrapolation	mass spectrometer PV-BNMS	Pioneer Venus	• Upper limit; see 135km data • Relative to CO_2	Mauersberger *et al.* 1979: p. 673
^{36}Ar	31 ppm	± 12 ppm	< 100 km	Compiled *in situ* data	mass spectrometers	Venera 11/12, Pioneer Venus	• von Zahn recommended value • Combines reported values with relative ^{36}Ar abundance of 44.2% to [Ar] on Venus	von Zahn *et al.* 1983: pp. 410, 424, 428 Tables XIII & XVI
^{36}Ar	30 ppm	+20, −10 ppm	< 24 km	*in situ*	LNMS	Pioneer Venus	Abundance relative to CO_2	Hoffman *et al.* 1980a: pp. 7886–7887, Table 2
^{38}Ar	6 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a: pp. 7886–7887, Table 2
^{40}Ar	31 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a: pp. 7886–7887, Table 2
^{40}Ar	33 ppm	+22, −11 ppm	< 25 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980b: pp. 7876–7877, Table 2
^{36}Ar	63 ppm	*see comment*	< 24 km	*in situ*	mass spectrometers	Venera 11/12	• Originally reported as 42±2% of total Ar (Ar_{total}= 150±50ppm)	Istomin *et al.* 1980a: p. 217
^{38}Ar	12 ppm	*see comment*	< 24 km	*in situ*	mass spectrometers	Venera 11/12	• Originally reported as 8±2% of total Ar (Ar_{total}= 150±50ppm)	Istomin *et al.* 1980a: p. 217
^{40}Ar	75 ppm	*see comment*	< 24 km	*in situ*	mass spectrometers	Venera 11/12	• Originally reported as 50±2% of total Ar (Ar_{total}= 150±50ppm) • ^{40}Ar abundance = ^{36}Ar+^{38}Ar	Istomin *et al.* 1980a: p. 217
^{38}Ar/^{36}Ar	0.18	± 0.02	< 24 km	*in situ*	LNMS	Pioneer Venus		Hoffman *et al.* 1980a: pp. 7886–7887, Table 3
^{38}Ar/^{36}Ar	0.197	± 0.002	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	• Originally reported as ^{36}Ar/ ^{38}Ar (5.07±0.05)	Istomin *et al* 1980b: pp. 4, 15

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
							• Expected instrument sensitivity 1ppm	
$^{40}Ar/^{36}Ar$	1.03	± 0.04	< 24 km	*in situ*	LNMS	Pioneer Venus		Hoffman *et al.* 1980a: pp. 7886–7887, Table 3
^{84}Kr	0.6 ppm	± 0.2 ppm	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	Relative to Ar	Istomin *et al.* 1980b: p. 16
^{84}Kr	0.5 – 0.8 ppm	-	23 – 1.5 km	*in situ*	mass spectrometers	Venera 11/12	Expected instrument sensitivity 1 ppm	Istomin *et al.* 1980a: p. 217
^{84}Kr	25 ppb	+3, −18 ppb	< 30 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Donahue *et al* 1981: p. 515 Donahue and Pollack 1983: Table I
^{84}Kr	10 – 100 ppb	-	26 km to surface	*in situ*	mass spectrometer	Venera 13	Preliminary results	Istomin *et al.* 1982: p. 214
^{84}Kr	< 0.2 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Upper limit mixing ratio if ^{36}Ar is 30 ppm	Hoffman *et al.* 1980a: p. 7887, Table 2
^{83}Kr	7.2 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 19 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 515
^{82}Kr	12.2 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 6 – 17 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 515
^{80}Kr	3.6 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 10.2 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 515
^{86}Kr	4.3 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Upper limit 9 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 515
$^{84}Kr/^{36}Ar$	0.004	± 0.002 (1σ)	< 24 km	*in situ*	LNMS	Pioneer Venus	Based on total 84 amu peak	Hoffman *et al.* 1980a: p. 7887, Table 2
$^{131+132}Xe$	10 – 100 ppb	-	26 km to surface	*in situ*	mass spectrometer	Venera 14	Preliminary results	Istomin *et al.* 1982: p. 215
^{128}Xe	1.5 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 4.7 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 514
^{129}Xe	9.5 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 35 ppb	Donahue *et al* 19817: p. 514

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Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	Reference (w/relevant pages)
							• Measured relative to ^{36}Ar	
^{130}Xe	4 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 10 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 514
^{131}Xe	14 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 40 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 514
^{132}Xe	10 ppb	-	< 30 km	*in situ*	LNMS	Pioneer Venus	• Range 0 – 47 ppb • Measured relative to ^{36}Ar	Donahue *et al* 1981: p. 514
^{132}Xe	1.9 ppbv	-	all	computed			Implied from $^{84}Kr/^{132}Xe$ value as cited in Pepin 1991	Pepin 1991: p. 18
$^{84}Kr/^{132}Xe$	0.004	± 0.002 (1σ)	< 24 km	*in situ*	LNMS	Pioneer Venus	Based on total 84 amu peak	Hoffman *et al.* 1980a: p. 7887, Table 2

[a] Acronyms: BNMS - Bus Neutral Mass Spectrometer; ONMS - Orbiter Neutral Mass Spectrometer; LNMS – Large probe Neutral Mass Spectrometer; LGC - Large probe Gas Chromatograph

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Table 4:

Reactive Gases

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
O_2	43.6 ppm	+25.2 ppm (3σ) ± 2.9 ppm (1σ)	51.6 km	*in situ*	LGC	Pioneer Venus	*Questioned by von Zahn et al. 1983*	Oyama *et al.* 1980; p. 7897, Table 2
O_2	16.0 ppm	+7.4 ppm (3σ) ± 0.9 ppm (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus	*Questioned by von Zahn et al. 1983*	Oyama *et al.* 1980; p. 7897, Table 2
O_2	< 20 ppm	-	< 42 km	*in situ*	gas chromatograph	Venera 12	• Originally written as 0.002% • Estimate due to instrument caveats	Gel'man *et al.* 1979: p. 5
O_2	< 30 ppm	-	52 km	*in situ*	LNMS	Pioneer Venus	Sample taken prior to clogged inlet	Hoffman *et al.* 1980b: pp. 7878, Table 2
O_2	< 30 ppm	-	22 km	*in situ*	LNMS	Pioneer Venus	Value is an upper limit due to subtractions of various contributions	Hoffman *et al.* 1980b: pp. 7878, Table 2
O_2	< 50 ppm	-	< 60 km	calculated	scanning spectrophotometers	Venera 12	Discussed in reference §2.5; upper limit added	Moroz 1981: Space Sci Rev. p 20, Table VI *(value not cited in orig ref Moroz 1979a)*
N_2	3.5 %	± 0.8 %	< 100 km	Compiled *in situ* data	mass spectrometers gas chromatographs	Pioneer Venus Venera 11/12	• Value recommended for < 45 km • *Potentially* varies with altitude	von Zahn *et al.* 1983: p. 359, Table II & V
N_2	5.38 v%	± 0.29 v% (1σ)	60–70 km	Remote data	neutron spectrometer	MESSENGER	Supports possible N_2 discontinuity at ~45km	Peplowski and Lawrence 2016: Abstract discussion
N_2	4 %	± 0.2 %	< 24 km	*in situ*	LNMS	Pioneer Venus		Hoffman *et al.* 1980a: p. 7888, Table 2
N_2	4.60 %	± 0.14% (3σ) ± 0.02% (1σ)	51.6 km	*in situ*	LGC	Pioneer Venus	Noted as most accurately determined component within this instrument	Oyama *et al.* 1980; p. 7896, Table 2
N_2	3.54 %	± 0.04% (3σ) ± 0.005% (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus	Noted as most accurately determined component within this instrument	Oyama *et al.* 1980; p. 7896, Table 2
N_2	3.41 %	± 0.01% (3σ) ± 0.002% (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus	Noted as most accurately determined component within this instrument	Oyama *et al.* 1980; p. 7896, Table 2
N_2	2.5 %	± 0.5%	< 42 km	*in situ*	gas chromatograph	Venera 12	Eight atmospheric samples	Gel'man *et al.* 1979: Table 1

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
N_2	4.5 %	± 1.3%	< 100 km	extrapolated	mass spectrometer PV-BNMS	Pioneer Venus		von Zahn *et al.* 1980: p. 7835
N_2	~4.0 %	-	26 km to surface	*in situ*	mass spectrometers	Venera 13/14		Istomin *et al.* 1982: p. 214
N_2	4.0 %	± 0.3%	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	A negligible background for methane existed in the regime of the chemically active component analysis	Istomin *et al.* 1980b: p. 12 *(COSPAR XXII)*
N_2	4.5 %	± 0.5%	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	*Superseded by value from* Istomin 1980b*?*	Istomin *et al.* 1980a: p. 216 *(COSPAR XXIII)*
H_2	10 ppm	-	< 140 km	derived from *in situ*	orbiter ion mass spectrometer	Pioneer Venus	Based on photochemical model	Kumar *et al.* 1981: abstract
H_2	Not detected*	-	52–22 km	*in situ*	LGC	Pioneer Venus, L	If present, upper limit < 10 ppm	Oyama *et al.* 1980; p. 7898, Table 3
H_2O	30 ppmv	±15 ppmv	0–45 km	*See comment*			In depth discussion; commonly cited value	Taylor *et al.* 1997. in Venus II pp.336–341, Table II
H_2O	30 ppm	± 6 ppm	33 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
H_2O	30 ppm	± 7.5 ppm	23.5 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
H_2O	30 ppm	±10 ppm	12 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
H_2O	3.5 – 15 ppm	-	0	Remote data	Fourier Transform Spectrometer	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
H_2O	40 ppm	-	≤ 55km	Remote data	Fourier Transform Spectrometer	Earth based Telescope	• Used best-fit spectrum model • Mixing ratio presented as 4×10^{-5}	Bézard *et al.* 1990:p. 510, Table 1
H_2O	30 ppm	+15, −10 ppm	30–40 km	Remote data	Fourier Transform spectrometer	Earth based Telescope	• High resolution, NIR Venus night side • 2.3 μm window	de Bergh *et al.* 1995: p. 81
H_2O	30 ppm	±10 ppm	15–25 km	Remote data	Fourier Transform spectrometer	Earth based Telescope	• High resolution, NIR Venus night side • 1.74 μm window	de Bergh *et al.* 1995: p. 82
H_2O	30 ppm	±15 ppm	0–15 km	Remote data	Fourier Transform spectrometer	Earth based Telescope	• High resolution, NIR Venus night side	de Bergh *et al.* 1995: p. 82

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Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
							• 1.1–1.3 μm window	
H_2O	20 ppm	-	surface	*in situ*	Photometers	Venera 11/12	Refinement of previous data	Moroz *et al.* 1979: p. 612
H_2O	100 ppm	-	< 55 km	selected value *(see comment)*	photometers gas chromatographs mass spectrometers	Venera 9,10,11,12 Pioneer Venus	• Paraphrased from text *[…likely correct value. The extent to which the various deviations from this mean value result from natural variability instrumental difficulties remains unknown.]* • Value chosen based on Moroz optical method, models by Pollack et al., and Craig et al. (see von Zahn refs therein)	von Zahn *et al.* 1983: pp. 370–375, Table III, VII
H_2O	0.135%	± 0.015% (3σ) ± 0.002% (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus	Data potentially skewed by trapped sulfuric acid droplet	Oyama *et al.* 1980; p. 7896, Table 2
H_2O	0.519%	± 0.068% (3σ) ± 0.008% (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus	Data potentially skewed by trapped sulfuric acid droplet	Oyama *et al.* 1980; p. 7896, Table 2
H_2O	< 0.06%	-	51.6 km	*in situ*	LGC	Pioneer Venus	Data potentially skewed by trapped sulfuric acid droplet	Oyama *et al.* 1980; p. 7896, Table 2
H_2O	< 0.1%	-	< 52 km	*in situ*	LN mass spectrometer	Pioneer Venus	Upper limit only	Hoffman *et al.* 1980b: pp. 7879, Table 2
H_2O	31 ppmv	± 2 ppmv (1σ)	30–40 km	Remote data	IR spectra (VIRTIS-H)	Venus Express	• dispersion order 5,6; 2.3 μm window	Marcq *et al.* 2008: p. 7, §3.2.3
H_2O	34 ppm	±10 ppm	32–42 km	Remote data	Fourier Transform spectrometer	Earth based Telescope	• Venus night side; 2.34–2.43 μm window • CO mixing ratio of 45 ppm at ~42 km	de Bergh *et al.* 1991: p. 548
HDO	1.3 ppm	± 0.2 ppm	32–42 km	Remote data	Fourier Transform spectrometer	Earth based Telescope	• Venus night side; 2.34–2.43 μm window • CO mixing ratio of 45 ppm at ~42 km	de Bergh *et al.* 1991: p. 548
CO_2	96.5 %	± 0.8 %	< 100 km	selected value *(see comment)*	-	-	• Typically quoted value • Based on previous N_2 measurements	von Zahn *et al.* 1983: pp. 336–336, Table II

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
							• From text: *[Assume that ratio $n(N_2)/n(CO)$ is constant throughout the lower and middle atmosphere (hut little observational support)]*	
CO_2	96.4%	± 1.0% (3σ) ± 0.1% (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus		Oyama *et al.* 1980; p. 7895, Table 2
CO_2	95.9%	+4.1%, −5.8% (3σ) ± 0.7% (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus		Oyama *et al.* 1980; p. 7895, Table 2
CO_2	95.4%	+14.6%, −20.1% (3σ) ± 2.5% (1σ)	51.6 km	*in situ*	LGC	Pioneer Venus		Oyama *et al.* 1980; p. 7895, Table 2
CO	45 ppm	±10 ppm	cloud layer	Remote data	Interferometer	Earth based Telescope	• Reported as CO/CO_2 ratio of 45 ppm • Value at the 'reflecting layer'	Connes *et al.* 1968: p. 742
CO	51 ppm	± 1 ppm (1σ)	cloud layer	Remote data	IR spectra	Earth based	• A review of Earth-based spectra. Reanalysis of Connes *et al.* 1968 data Presumes well-mixed atmosphere	Young 1972: p. 654
CO	30 ppm	-	≤ 22 km	Remote data	Fourier Transform Spectrometer	Earth based Telescope	• Used best-fit spectrum model • Mixing ratio noted originally as 3×10^{-5}	Bézard *et al.* 1990: p. 510, Table 1
CO	45 ppm	-	42 km	Remote data	Fourier Transform Spectrometer	Earth based Telescope	• Used best-fit spectrum model • Mixing ratio noted originally as 4.5×10^{-5}	Bézard *et al.* 1990: p. 510, Table 1
CO	32.2 ppm	+61.7, −22.2 ppm (3σ) ± 7.2 ppm (1σ)	51.6 km	*in situ*	LGC	Pioneer Venus	Direct measurement	Oyama *et al.* 1980; p. 7897, Table 2
CO	30.2 ppm	± 18 ppm (3σ) ± 2.1 ppm (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus	Direct measurement	Oyama *et al.* 1980; p. 7897, Table 2

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
CO	19.9 ppm	± 3.12 ppm (3σ) ± 0.4 ppm (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus	Direct measurement	Oyama *et al.* 1980; p. 7897, Table 2
CO	28 ppm	± 14 ppm	< 42 km	*in situ*	gas chromatography	Venera 12	• Eight atmospheric samples • Results presented as $(2.8\pm1.4)\times10^{-3}$ %	Gel'man *et al.* 1979: Table 1
CO	24 – 2 ppmv	± 3, 2 ppmv (1σ) *respectively*	36 km	Remote data	IR spectra (VIRTIS-H)	Venus Express	• latitudinal variability • dispersion order 6; 2.3 µm window	Marcq *et al.* 2008: p. 6, §3.2.1
CO	13.8 – 33.2 ppmv	± 4 ppmv	36 km	Modeled from Remote data	IR spectra (VIRTIS-M-IR)	Venus Express	• possible variability in troposphere • band ratio technique; 2.3 µm window	Tsang *et al.* 2009: p. 436, §2.2.3
CO	23 ppm	± 5 ppm	36 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	• Radiative transfer program/model with two Venus nightside emission spectra • Gradient: 1.20 ± 0.45 ppm/km	Pollack *et al.* 1993: Table IV
CO	17 ppmv	± 1 ppmv	12 km	*in situ*	gas chromatography	Venera 11/12		Marov et al 1989. In The Planet Venus, pp. 25–67. *Noted in LF1998*
COS [sic]	40 ppmv	± 20 ppmv	29–37 km	*in situ*	gas chromatography	Venera 13/14	$(4\pm2)\cdot10^{-3}$ volume concentration, %	Mukhin *et al.* 1983: Table 2, p 171
OCS	4.4 ppm	± 1 ppm	33 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	• Radiative transfer program/model with two Venus nightside emission spectra • Gradient: −1.58 ± 0.30 ppm/km	Pollack *et al.* 1993: Table IV
OCS	0.25 ppm	-	≤ 50 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	• Used best-fit spectrum model • Mixing ratio noted originally as 2.5×10^{-7}	Bézard *et al.* 1990: p. 511, Table 1

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
OCS	14 ppmv	6 ppmv	30 km	Remote data	IR spectra	Earth based telescopes		Bézard 1994. Comunication at the 30th COSPAR Scientific Assembly; *Cited in Taylor et al in Venus II*, p. 347
OCS	0.35 ppmv	± 0.1 ppmv	38 km	Remote data	IR spectra	Earth based telescopes		Bézard 1994. Comunication at the 30th COSPAR Scientific Assembly; *Cited in Taylor et al in Venus II*.p. 347
OCS	2.5 – 4 ppmv	± 1 ppmv (1σ)	33 km	Remote data	IR spectra (VIRTIS-H)	Venus Express	• latitudinal variability; CO anticorrelated • dispersion order 5,6; 2.3μm window	Marcq *et al.* 2008: p. 7, §3.2.2
OCS	*Not detected	-	52–22 km	*in situ*	LGC	Pioneer Venus	If present, upper limit < 2 ppm	Oyama *et al.* 1980; p. 7898, Table 3
OCS	< 3 ppm	-	> 24 km	*in situ*	LNMS	Pioneer Venus	Debatable data due to sulfuric acid droplet	Hoffman *et al.* 1980a; p. 7886, Table 2
OCS	< 500 ppm	-	< 20 km	*in situ*	LNMS	Pioneer Venus	Debatable data due to sulfuric acid droplet	Hoffman *et al.* 1980a; p. 7886, Table 2
SO_2	4 ppm	-	58 km	model	UV spectrometer	Pioneer Venus	Model constrained using PV-OUVS data	Winick and Stewart 1980: p. 7854
SO_2	180 ppm	± 70 ppm	42 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
SO_2	130 ppmv	± 50 ppmv (1σ)	35 km	Remote data	IR spectra (VIRTIS-H)	Venus Express	• dispersion order 5,6; 2.3 μm window • assume uniform abund vertical profile	Marcq *et al.* 2008: p. 7, §3.2.4
SO_2	130 ppm	± 60 ppm	< 42 km	*in situ*	gas chromatography	Venera 12	• Eight atmospheric samples • Results presented as $(1.3\pm0.6)\times10^{-2}$ %	Gel'man *et al.* 1979: Table 1
SO_2	185 ppm	+350, −155 ppm (3σ) ± 43.1 ppm (1σ)	21.6 km	*in situ*	LGC	Pioneer Venus		Oyama *et al.* 1980; p. 7898, Table 2

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SO_2	176 ppm	+2000, 0 ppm (3σ) + 296, 0 ppm (1σ)	41.7 km	*in situ*	LGC	Pioneer Venus		Oyama *et al.* 1980; p. 7898, Table 2
SO_2	< 600 ppm	-	51.6 km	*in situ*	LGC	Pioneer Venus		Oyama *et al.* 1980; p. 7898, Table 2
SO_2	< 300 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Upper limit value due to clogged inlet	Hoffman *et al.* 1980a: pp. 7888–7889, Table 2
SO_2	<10 ppm	-	55 km	*in situ*	LNMS	Pioneer Venus		Hoffman *et al.* 1980a: pp. 7888–7889, Table 2
SO_2	150 ppm	-	52 km	*in situ*	UV spectrometer	VEGA 1	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	65 ppm	-	52 km	*in situ*	UV spectrometer	VEGA 2	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	125 ppm	-	42 km	*in situ*	UV spectrometer	VEGA 1	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	140 ppm	-	42 km	*in situ*	UV spectrometer	VEGA 2	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	38 ppm	-	22 km	*in situ*	UV spectrometer	VEGA 1	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	38 ppm	-	22 km	*in situ*	UV spectrometer	VEGA 2	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	25 ppm	± 2 ppm	12 km	*in situ*	UV spectrometer	VEGA 1	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	20 ppm	-	12 km	*in situ*	UV spectrometer	VEGA 2	Gradient discussed	Bertaux *et al.* 1996: p. 12737, Table 4
SO_2	130 ppm	± 40 ppm	35–45 km	Remote data	spectrometer	Earth based	Venus nightside emission; 2.3 μm window	Bézard *et al.* 1993: p. 1588
SO_2	150 ppm	-	22 km	Compiled *in situ* data	UV spectrometer mass spectrometers gas chromatograph	Venera 12 Pioneer Venus	von Zahn recommended value	von Zahn *et al.* 1983: pp. 390–392, Tables III & X
SO_2	<10 ppm	-	55 km	Compiled *in situ* data	UV spectrometer mass spectrometers gas chromatograph	Venera 12 Pioneer Venus	von Zahn recommended value	von Zahn *et al.* 1983: pp. 390–392, Tables III & X
SO_2	*Not detected	-	23 – 4 km	*in situ*	mass spectrometers	Venera 11/12	If present, upper limit < 25 ppm	Istomin *et al.* 1980b: p. 17
SO	20 ppb	± 10 ppb	cloud-top	Remote data	LWP Camera	Intl UV Explorer		Na *et al.* 1990: abstract & p. 7490
H_2S	3 ppm	± 2 ppm	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a: pp. 7789, Table 2

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
H_2S	Not detected*	-	52–22 km	*in situ*	LGC	Pioneer Venus	If existent, upper limit < 2 ppm	Oyama *et al.* 1980; p. 7898, Table 3
H_2SO_4	8 ppmv	-	46 km	Remote data	microwave: VLA	Earth based	Rapidly declines below this altitude	Jenkins *et al.* 2002: p.324
CH_4	Not detected*	-	22–52 km	Data	LGC	Pioneer Venus	If present, upper limit < 0.6 ppm	Oyama *et al.* 1980; p. 7898, Table 3
CH_4	980 ppm	-	> 50 km	*in situ*	LNMS	Pioneer Venus	Observation questioned; no plausible explanation. See discussion in reference.	Donahue and Hodges 1993: p. 592
CH_4	2800 ppm	-	Near surface	*in situ*	LN mass spectrometer	Pioneer Venus	Observation questioned; no plausible explanation. See discussion in reference.	Donahue and Hodges 1993: p. 592
CH_4	< 0.1 ppm	-	30 km	Remote data	spectrometers	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission IR spectra	Pollack *et al.* 1993: Table IV
CH_4	< 2.0 ppm	-	24 km	Remote data	spectrometers	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission IR spectra	Pollack *et al.* 1993: Table IV
C_2H_4	Not detected*	-	22–52 km	*in situ*	LGC	Pioneer Venus	If existent, upper limit < 1 ppm	Oyama *et al.* 1980; p. 7898, Table 3
C_2H_6	~2 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Deduced from ratio to ^{36}Ar	Hoffman *et al.* 1980a: pp. 7789, Table 2
C_2H_6	Not detected*	-	22–52 km	*in situ*	LGC	Pioneer Venus	If existent, upper limit < 1 ppm	Oyama *et al.* 1980; p. 7898, Table 3
C_3H_6	Not detected*	-	22–52 km	*in situ*	LGC	Pioneer Venus	If existent, upper limit < 5 ppm	Oyama *et al.* 1980; p. 7898, Table 3
Cl	<10 ppm	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Upper limit; deduced from measurements.	Hoffman *et al.* 1979b: p. 50 Hoffman *et al.* 1980a: Table 2
HCl	0.1 ppm	± 0.03 ppm (1σ)	70–75 km	Remote data	SOIR	Venus Express	*orbit 136*	Bertaux *et al.* 2007: p. 648
HCl	0.17 ppm	± 0.03 ppm (1σ)	70–75 km	Remote data	SOIR	Venus Express	*orbit 247*	Bertaux *et al.* 2007: p. 648
HCl	0.4 ppmv	-	cloud-top	Remote data	Fourier Transform Spectrometer	CFHT Earth based	Altitude at 35mbar level	de Bergh *et al.* 1989: abstract 6.09P
HCl	0.5 ppm	-	~18 km	Remote data	Fourier Transform Spectrometer	Earth based telescopes	• Used best-fit spectrum model • Mixing ratio presented as 5×10^{-7}	Bézard *et al.* 1990: p. 511, Table 1

Element	Mole Fraction	Error	Altitude	Technique	Instrument[a]	Mission	Comment	References (w/relevant pages & tables)
HCl	0.48 ppm	± 0.12 ppm	23.5 km	Remote data	spectrometers	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
HCl	0.4 ppm	-	~64 km	model			Value based on chemical modelling and related observations	von Zahn *et al.* 1983: pp. 401–403, Table III
HCl	0.5 ppmv	± 0.15 ppmv	15–30 km	Remote data	IR spectra	Earth based		Bézard 1994. Communication at the 30th COSPAR Scientific Assembly; *Cited in Taylor et al in Venus II*.p. 347
HF	0.005 ppm	-	~64 km	model			Based on chemical modelling and related observations	von Zahn *et al.* 1983: p. 403, Table III; Parisot and Moreels 1984: p. 73
HF	0.001–0.003 ppb	-	75–85 km	Remote data	SOIR	Venus Express	*orbit 114*	Bertaux *et al.* 2007: p. 648
HF	5 ppbv	± 2 ppbv	30–40 km	Remote data	IR spectra	Earth based		Bézard 1994. Communication at the 30th COSPAR Scientific Assembly; *Cited in Taylor et al in Venus II*.p. 347
HF	0.001–0.005 ppm	-	33.5	Remote data	Fourier Transform Spectrometer	Earth based telescopes	Radiative transfer program/model with two Venus nightside emission spectra	Pollack *et al.* 1993: Table IV
HF	4.5 ppb 0.0045 ppm	-	~32 km	Remote data	Fourier Transform Spectrometer	Earth based Telescope	• Used best-fit spectrum model • Mixing ratio presented as 4.5×10^{-9}	Bézard *et al.* 1990: p. 510, Table 1
N_2O	*Not detected	-	22–52 km	*in situ*	LGC	Pioneer Venus	If present, upper limit < 10 ppm; optimum case	Oyama *et al.* 1980; p. 7898, Table 3
Hg	*Not detected	-	< 24 km	*in situ*	LNMS	Pioneer Venus	Upper limit of 5ppm reported but discussion implies uncertain detection.	Hoffman *et al.* 1980a: pp. 7789, Table 2

[a]Acronyms: BNMS - Bus Neutral Mass Spectrometer; ONMS - Orbiter Neutral Mass Spectrometer; LNMS – Large probe Neutral Mass Spectrometer; LGC - Large probe Gas Chromatograph

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Table 5:

Isotopic Ratios of the Reactive Gases

Element	Ratio	Error	Altitude	Technique	Instrument	Mission	Comment	References (w/relevant pages & tables)
D/H in H_2O	0.016	± 0.002	~54 km	*in situ*	mass spectrometer LNMS	Pioneer Venus	Measured when inlets were clogged with H_2SO_4 droplets	Donahue *et al.* 1982: p. 630, 633
D/H in H_2O	0.019	± 0.006	32–42 km	Remote data	Fourier Transform spectrometer	Earth based Telescope	• Venus night side; 2.34–2.43 µm window • CO mixing ratio of 45 ppm at ~42 km • D/H equal to ½ × [HDO]/[H_2O]	de Bergh *et al.* 1991: p. 548
D/H	0.025	± 0.005	54 km	*in situ*	Mass Spectrometer	Pioneer Venus	*Derived from H_2SO_4 droplets trapped at 54km*	Atreya, personal communication
$^{12}C/^{13}C$ in CO_2	86	± 12	Cloud tops	Remote data	Michelson Interferometer	Earth-based	Derived from $^{13}CO_2$ abundance	Bézard *et al.* 1987: p.623 & Table IV
$^{12}C/^{13}C$ in CO_2	89.3	± 1.6	23 – 1 km	*in situ*	mass spectrometers	Venera 11/12	• Presented as $^{13}C/^{12}C$: 1.12±0.02 × 10^{-2} • Includes contributions from CH^+ ions	Istomin *et al.* 1980b: p. 13
$^{12}C/^{13}C$ in CO_2	84.0	± 4.2	23 – 1 km	*in situ*	mass spectrometer LNMS	Pioneer Venus	Presented as $^{13}C/^{12}C \leq 1.19 \pm 0.06 \times 10^{-2}$	Hoffman *et al.* 1980a; p. 7887, Table 3
$^{14}N/^{15}N$	Earth atmos value	± 20%	< 100 km	*in situ* derive	Mass Spectrometer	Pioneer Venus	Assumes well mixed atmosphere. $^{14}N/^{15}N$ = 273 ± 56; see ref note	Hoffman *et al* 1979: abstract Value in Lodders&Fegley 1998: Table 5.5
$^{18}O/^{16}O$	2.0 × 10^{-3}	± 0.1 × 10^{-3}	< 24 km	*in situ*	mass spectrometer LNMS	Pioneer Venus	Contributions from CO_2 and SO_2	Hoffman *et al.* 1980a; p. 7888, Table 3
$^{18}O/^{16}O$ in CO_2	0.002	± 0.0125	Cloud tops	Remote data	Michelson Interferometer	Earth-based	Derived from $^{12}C^{16}O^{18}O$ abundance Reported as $^{16}O/^{18}O$= 500± 80	Bézard *et al.* 1987: p. 623 & Table V
$^{35}Cl/^{37}Cl$ in HCl	2.9	± 0.3	Cloud tops	Remote data	IR spectra	Earth-based	Primary data presented in Connes *et al.* 1967. Calculated from HCl lines in the 2–0 R-Branch (Table 1, p.1231) [value 2.869]	Cited value Young 1972: p. 640; Connes *et al.* 1967 orig data

[a] Acronyms: LNMS – Large probe Neutral Mass Spectrometer