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Hypothesis Paper

A Sulfur-Based Survival Strategy for Putative Phototrophic Life in the Venusian Atmosphere

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ABSTRACT

Several observations indicate that the cloud deck of the venusian atmosphere may provide a plausible refuge for microbial life. Having originated in a hot proto-ocean or been brought in by meteorites from Earth (or Mars), early life on Venus could have adapted to a dry, acidic atmospheric niche as the warming planet lost its oceans. The greatest obstacle for the survival of any organism in this niche may be high doses of ultraviolet (UV) radiation. Here we make the argument that such an organism may utilize sulfur allotropes present in the venusian atmosphere, particularly S_8, as a UV sunscreen, as an energy-converting pigment, or as a means for converting UV light to lower frequencies that can be used for photosynthesis. Thus, life could exist today in the clouds of Venus. Key Words: Venusian atmosphere—Sulfur—Phototropic life—Extreme environment—Microbial life—Venus. Astrobiology 4, 11–18.

A NUMBER OF ARGUMENTS have been advanced previously in support of the possibility of microbial phototrophic life in the venusian atmosphere (Sagan, 1961; Grinspoon, 1997; Schulze-Makuch and Irwin, 2002; Schulze-Makuch and Irwin, 2004). These include the following observations: (1) The clouds of Venus are much larger, more continuous, and stable than the clouds on Earth; (2) the atmosphere is in chemical disequilibrium, with H_2 and O_2, and H_2S and SO_2 coexisting; (3) the lower cloud layer contains nonspherical particles comparable in size to microbes on Earth; (4) temperatures of 300–350 K, a pH of approximately 0, and a pressure of about 1 bar are conditions tolerated by some microbes on Earth; (5) the super-rotation of the atmosphere enhances the potential for photosynthetic reactions by reducing the time duration without light (a day–night cycle of 4–6 Earth days compared with 117 Earth days on the surface); (6) an unknown absorber of ultraviolet (UV) energy has been detected in the venusian atmosphere; and (7) while water is scarce on Venus, water vapor concentrations reach several hundred ppm in the lower cloud layer.

Planetary atmospheres traditionally have not been considered to be likely environments for permanent habitation. However, recent research calls that assertion into question. For example, Sattler *et al.* (2001) showed that bacteria in cloud

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droplets at high altitudes on Earth are actively growing and reproducing, and concluded that the limiting step for the persistence of microbial life in cloud droplets is residence time in the atmosphere. Particles in the venusian atmosphere have much longer residence times than in Earth's atmosphere, on the order of months compared with days on Earth (Esposito *et al*., 1983; James *et al*., 1997). For water-based life, the discontinuous and cold clouds of Earth represent, in many ways, a more extreme environment than those of Venus. Thus, if microbial life has gained a foothold in Earth's atmosphere, the more favorable conditions of the atmosphere on Venus should certainly make it a suitable habitat for microbial life. If life arose or was transported to Venus at an earlier stage in its planetary history when liquid water may have persisted on the surface (Jakosky, 1998; Owen, 2000), descendents of those early forms could have adapted to the increasingly warm, dry, and acidic atmosphere through directional selection that would have favored retention of characteristics suitable for those conditions (Schulze-Makuch and Irwin, 2004).

Two major obstacles to the persistence of life in the venusian atmosphere would have remained, however: the low pH, and the high doses of UV radiation. The low pH limit of terrestrial life is not known, but recently discovered acidophiles suggest that this environmental constraint may not be prohibitive. For example, the archaeon *Ferroplasma acidarmanus* thrives at pH 0 (Edwards *et al*., 2000). Also, microbial densities were found to be highest in sulfuric acid hot springs of pH 1–2, among a large sample of various types of hot springs in New Mexico, USA (Rzonca and Schulze-Makuch, 2003).

UV radiation is damaging to biological macromolecules. However, adaptation to a UV-rich and water-poor environment through directional selection is possible. Common strategies for terrestrial organisms to protect against UV radiation include specialized organic pigments such as carotenoids and scytonemin (Wynn-Williams *et al*., 2002), protection by layers of soil or water (Pierson *et al*., 1993; Wynn-Williams and Edwards, 2000), and shielding by organic compounds derived from dead cells (Marchant *et al*., 1991). However, as an alternative to damage prevention some microbes such as cyanobacteria and *Deinococcus radiodurans* use highly efficient mechanisms to repair DNA and resynthesize UV-sensitive proteins (Battista, 1997; Ehling-Schulze and Scherer, 1999). Another intriguing example of adaptation to high UV flux is the fungus *Fusarium alkanophylum*. Marcano *et al*. (2002) showed experimentally that several phenotypes exhibit optimal growth under high doses of UV radiation with minimum water requirements, provided that the growth media contained proteins with sulfur linkages.

If microbial life exists in the venusian atmosphere, a mechanism has to be employed to cope with high doses of UV radiation. Given the scarcity of water in the venusian atmosphere, microbes may assimilate water vapor from hydrated sulfur compounds [$H_2SO_4 \cdot n(H_2O)$] or from the atmosphere, similar to the assimilation of carbon from CO_2 by microbes in Earth's atmosphere. However, because water is not a good UV absorber in minute concentrations, some other shielding is needed. A compound that absorbs in the UV region and is capable of donating electrons to appropriate electron acceptors might have been favoured by natural selection—in particular, since it would both protect against UV radiation and be utilized directly as a powerful energy source. Various compounds may exhibit these properties and be available under venusian conditions. One such compound, cycloocta-sulfur (S_8), is most promising in that it is the most thermally stable form of elemental sulfur and does not react with sulfuric acid. Its strong UV absorption is caused by 16 delocalized electrons in the S_8-ring (Block, 1978). Cycloocta-sulfur absorbs strongly in the UV wavelengths and reemits in the visible wavelengths (Spear and Adams, 1965). It has an absorption maximum at 285 nm near the UV wavelengths most damaging to cells (~240–280 nm, Fig. 1). This absorption peak is so strong that S_8-crystals are opaque below 350 nm (Meyer *et al*., 1972). Thus, a sulfuric acid coating that just engulfs a few monolayers of S_8 would absorb a very significant portion of the UV radiation encountered by a microorganism.

Detailed simulations of infrared absorption in the venusian clouds (Grinspoon *et al*., 1993) showed that the large "mode 3" particles, which make up most of the mass of the cloud deck, may be composed of an unknown, non-absorbing core material that makes up to 50% by volume of the particles. Radio occultation results also support the idea that mode 3 particles are composed of nonabsorbing material coated with sulfuric acid (Cimino, 1982). The high surface temperature and

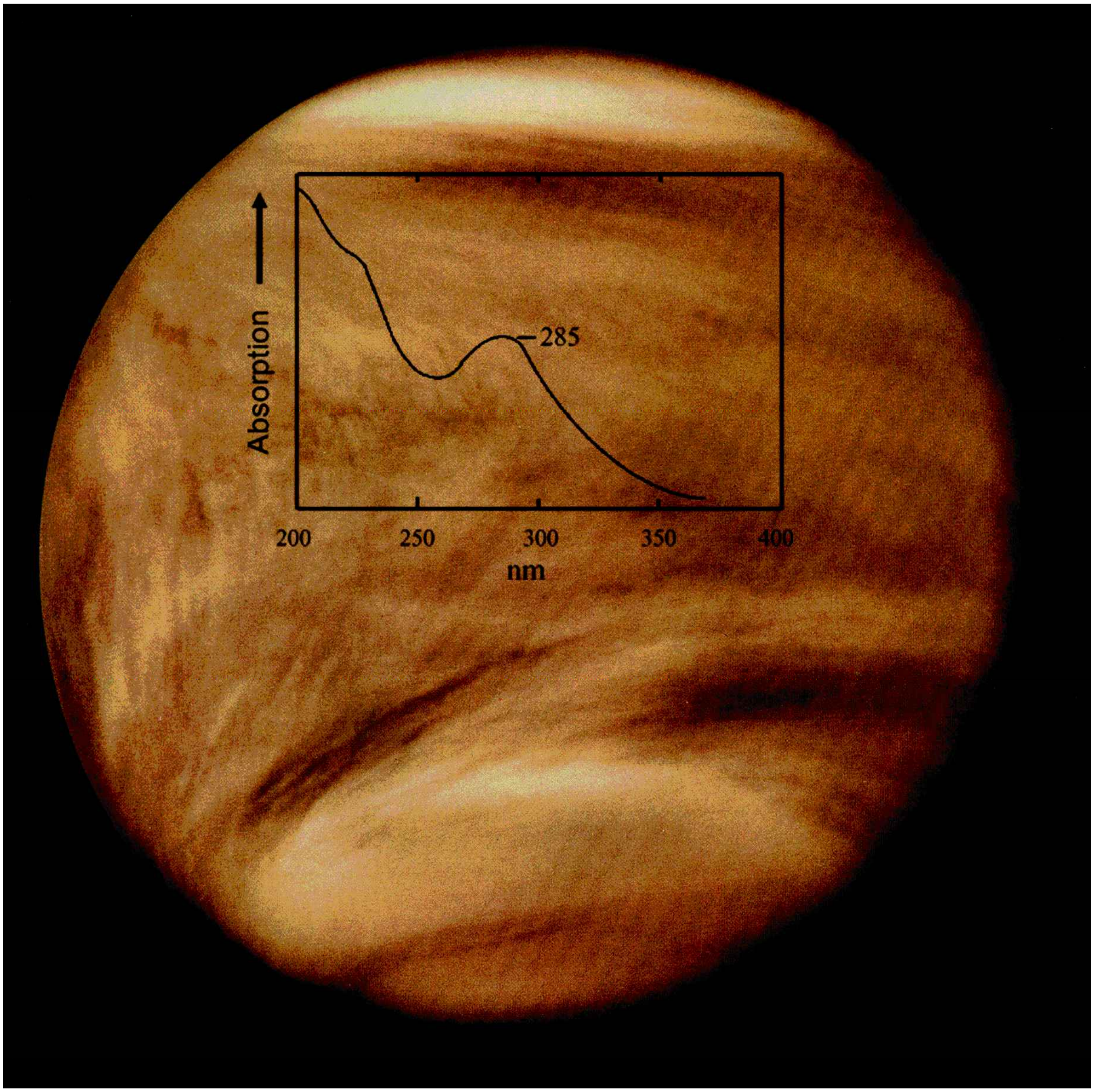

FIG. 1. Venus as it appears in reflected UV light. Dark areas trace cloud top winds and are produced by absorption of solar UV below by SO_2 and most likely various allotropes of sulfur. Source: NSSDC, http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-venus.html, image pvo_uv_790205. **Inset:** Absorption of a thin film of S_8 at 298 K (modified from Clark, 1963).

reduced crust on Venus (relative to Earth) ensures that sulfur gases in various forms are abundant in the atmosphere. Sulfur exists in the atmosphere of Venus, mostly as SO_2 and COS (von Zahn *et al.*, 1983), but also in sulfuric acid aerosols that occur in the three major global cloud decks (James *et al.*, 1997). The clouds are present in the atmosphere from roughly 48 km to 65 km altitude, and have a columnar S mass of approximately 5 mg/cm^2. The atmosphere as a whole is a far larger reservoir of S, with an average columnar mass density of about 20 g/cm^2. These gases were measured *in situ* by the Pioneer Venus Large Probe Gas Chromatograph (Oyama *et al.*, 1980), and by the Vega 1 and 2 spectrophotometers (Berteau *et al.*, 1996).

Sulfur dioxide at the cloud tops is readily seen in reflected solar UV as contrast features that trace middle atmosphere motions (Fig. 1). In addition to the strong absorption of UV sunlight by SO_2, absorption of visible wavelength occurs throughout the upper cloud deck. The visible-wavelength features appear to trace the UV absorption by SO_2, but come and go on timescales of hours. SO_2 cannot account for this absorption, since it absorbs only at wavelengths shorter than 3,200 Å. A compelling candidate for this absorber is elemental sulfur. Toon *et al*. (1982) showed that the existence of S_8 is photochemically likely in the venusian atmosphere, and that it dissociates into the shorter-chain sulfur molecules S_3 and S_4. These allotropes absorb in the visible and are metastable on the same timescales as the contrast features seen in visible images of reflected sunlight. The derivation of S_x from SO_2 in the upper clouds of Venus provides a natural explanation for its spatial association with the SO_2 UV contrast features observed (Toon *et al*., 1982).

The upper clouds should be about 8% elemental sulfur by mass, drawn from a reservoir of S_x vapor, based on a chemical and microphysical cloud model by Toon *et al*. (1982). The calculated cloud particle size distributions are able to explain the optical properties of the upper clouds, particularly the large backscattering cross section of the cloud aerosols.

In the atmosphere below the cloud layers, S_8 should decompose thermochemically to S_4, S_3, and finally to S_2 near the surface (Prinn, 1985a). San'ko (1980) analyzed the scanning spectrophotometer data from the descending Venera 11 and 12 spacecrafts and concluded that strong absorption at 4,500 and 6,000 Å in the lower atmosphere was due to an elemental S_x abundance of about 20 ppb.

The abundance of S_x in the atmosphere of Venus, based on data from the Venera 11 and 12 spacecraft and the cloud model of Toon *et al*. (1982), is synthesized in Fig. 2. With S making up about 8% of the upper cloud aerosols, its density there is on the order of 10^{-10} g/cm^3. Assuming a concentration of 20 ppb S below the clouds (San'ko, 1980), the mass density varies from approximately 4×10^{-11} to 1×10^{-9} g/cm^3. S_8 is the most stable form within the clouds, while shorter-chain allotropes are more common both above and below the clouds (Fig. 2).

Recently, it was suggested that for early Earth, S_8 may have been produced by consecutive reaction of sulfur compounds with UV radiation and that under very reducing conditions or high SO_2 flux, all sulfur could be converted to S_8 (Pavlov *et al*., 2002). The venusian atmosphere is currently not that reducing, and SO_2 fluxes, while unconstrained, are probably moderate. A crude estimate can be made as follows:

If SO_2 with a current abundance of 130 ppm (Pollack *et al*., 1993) is in steady state with outgassing on a timescale of a few tens of millions of years (Bullock and Grinspoon, 2001), this implies a current outgassing source of a few 10^{12} g of SO_2/year. This number is consistent with Magellan-derived resurfacing-rate estimates of approximately 0.4 km^3 of magma/year (Bullock *et al*., 1993), with an assumed sulfur weight percent of 0.2, equivalent to terrestrial Ocean Island Basalts. In the volcanically more active phases suggested for earlier epochs from analysis of Magellan images (Bullock *et al*., 1993), major amounts of sulfur could have been converted to S_8 and remained relatively stable thereafter. The suggested evidence of S_8 aerosols in Earth's Archean atmosphere points to a common environmental condition for both early Earth and Venus, from which similar adaptation strategies could have evolved, or migrated through "impact transpermia" (Melosh, 1988).

Alternatively, the elemental sulfur could be microbially produced via a photosynthetic reaction used by microbes early in the history of the Earth, in which hydrogen sulfide is oxidized to elemental sulfur and carbon dioxide is reduced to organic carbon (Eq. 1):

$$2\ H_2S + CO_2 + \text{light} \rightarrow \text{“}CH_2O\text{”} + H_2O + 2\ S \qquad (1)$$

Many organisms using this reaction thrive in marine sediments of warm seas, soils, and hot springs (*e.g*., Vethanayagam, 1991; Bryantseva *et al*., 2000); thus they may have been ideal inhabitants for a warm proto-ocean on early Venus. The oxidized sulfur product given in Eq. 1 could then be polymerized to S_8. Thus, Reaction 1 is a plausible pathway for microbial life on Venus. Several photosynthetic microbes that use H_2S as their electron source deposit sulfur outside the cell. These include green sulfur bacteria, some purple sulfur bacteria, and some cyanobacterial species (*e.g*., Pierson *et al*., 1987; Tortora *et al*., 2001). Some of these bacteria are known to thrive in moderately acidic environments, but none is known to thrive below a pH of 4.5 (Castenholz, 1984; Wahlund *et al*., 1991; Zaar *et al*., 2003). Putative venusian microbes might deposit elemental sulfur on the outside of their cells to convert poten-

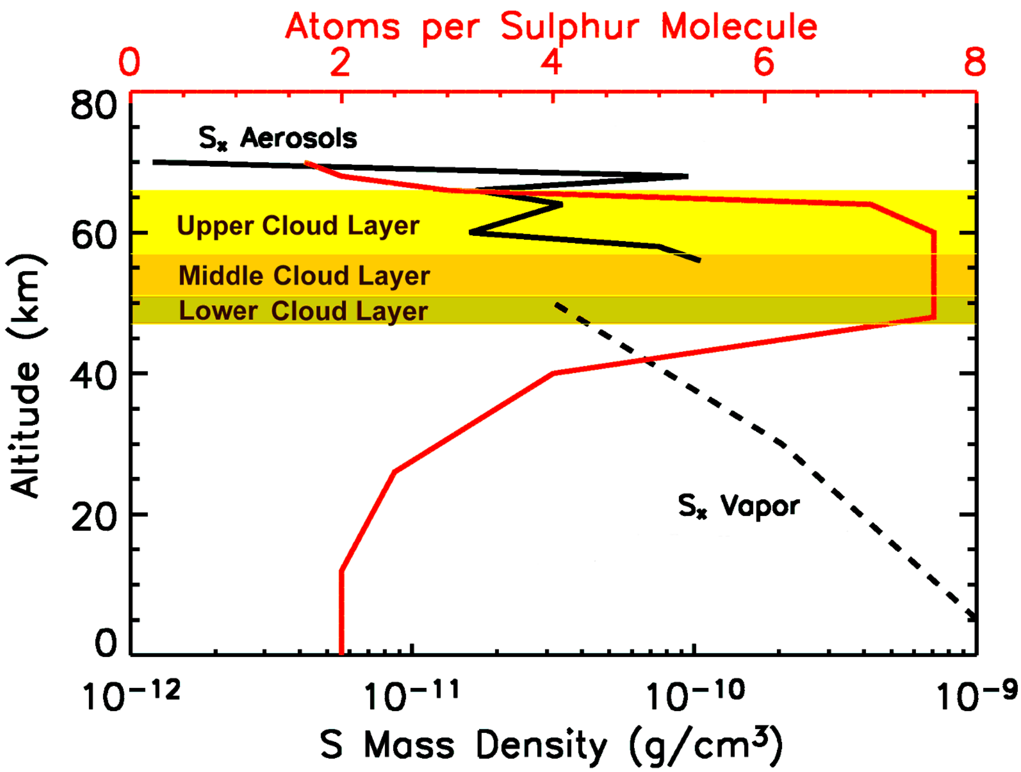

FIG. 2. Expected elemental sulfur abundance in the atmosphere of Venus. The solid black curve depicts the density of S_x (S_1–S_8) in aerosols of the venusian upper clouds from the cloud chemical/microphysical model by Toon *et al.* (1982). The lower dashed black line is the total S_x vapor density deduced from the Venera 11 and 12 scanning spectrophotometer experiments (San'ko, 1980). S_2 is the dominant form of sulfur vapor below 20 km, as can be seen by the red line showing the average number of S atoms per S molecule. S_8 is stable in the middle and lower clouds, while photochemical processes generate shorter-chain S allotropes in the upper cloud layers. The red line is based on Toon *et al.* (1982) for the cloud region and on Prinn (1985b) for the lower atmosphere.

tially harmful UV radiation to electromagnetic frequencies that are usable for photosynthesis, or harvest the energy of UV photons through conversion to appropriate electron donors. Alternatively, they may just utilize sulfur allotropes as "sunscreen" and utilize visible light for photosynthesis. In proposing photosynthesis as the bioenergetic mechanism for the support of putative microbial life in the clouds of Venus, we do not mean to imply the same molecular processes of photosynthesis as they occur in phototrophs on Earth. Indeed, as life has evolved in a much less acidic environment on this planet, selection has favored mechanisms that operate at neutral pH values and are non-functional at high acidity. On Venus, however, forms of life may have evolved a quite different molecular machinery to deal with the progressively acidifying conditions.

Alternatively, several chemoautotrophic reactions are plausible such as the oxidation of carbon monoxide to carbon dioxide coupled to the reduction of sulfur dioxide to hydrogen sulfide or carbonyl sulfide (for details, see Schulze-Makuch and Irwin, 2002). Many thermophilic and thermoacidophilic microbes on Earth are known to use sulfur in their metabolic pathways (*e.g.*, Amend and Shock, 2001), and many sulfur-utilizing chemoautotrophic bacteria do thrive at extremely low pH values (*e.g.*, *Thiobacillus* sp.). Furthermore, Pasteris *et al.* (2001) showed that submicrometer- to several micrometer-diameter vesicles in two species of sulfur-oxidizing bacteria consisted of S_8 in an extremely fine-grained microcrystalline form.

It might be worth noting that tolerances to UV radiation and desiccation tend to occur together in microbial species [*e.g.*, *D. radiodurans* (Makarova *et al.*, 2001)], and these are traits necessary for surviving interplanetary transfer of life. Therefore, instead of life originating independently on Venus, ancestral photoautotrophic or chemoautotrophic organisms from Earth or Mars could have been delivered by impact panspermia, when the planetary environments on all three planets were likely to have been very similar. Early Venus with an ocean most likely would not have been particularly acidic, although it would still have been a harsh UV environment (Kasting *et al*., 1988; Cockell, 1999, 2000). The acidity of the atmosphere would have increased during the first 600 million years or so after the formation of Venus, as the planet dried out (Kumar *et al*., 1983). However, this timescale is very uncertain, and Venus may have remained wet and relatively pH neutral for a billion years or more. It is entirely possible that non-acidophilic organisms were transferred during the late heavy bombardment and adapted to the changing (acidic, UV) environments on Earth and Venus separately, or that photosynthesis developed independently on Venus from transported chemoautotrophic organisms.

The use of elemental sulfur, and particularly S_8, as a protective coating against UV radiation by microbes in the Venusian atmosphere would explain why no absorption features of hydrocarbons were observed previously (Plummer, 1969), even though microbial life may have been present in the clouds of Venus. Sulfur compounds used in this way could possibly be identified through remote sensing of their unique isotopic ratios, though the biomass levels supportable by such low concentrations of S may make that unfeasible. Preferable, therefore, would be an analysis of the core material of the mode 3 particles. A sample return mission from the cloud layers of Venus is technologically feasible (Schulze-Makuch *et al*., 2002), and conceivably could yield evidence of extraterrestrial life sooner and more easily than from the more remote candidate habitats of Mars and Europa.

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ABBREVIATION

UV, ultraviolet.

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