



## Active Spectrometry of the Ultraviolet Absorption Within the Venus Atmosphere

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### 3. PRELIMINARY EXPERIMENTAL RESULTS

The VM-4 humidity analyzer was installed in the lower part of each Vega descent capsule, mounted on the landing ring. At about 62 km above the Venus surface a command from the on-board timer-programmer turned on the hygrometers. The sensors were unsealed and power was fed to the instruments. From that point onward, information from the VM-4 was transmitted through the TM channels at a rate of 2.3 Hz.

On each descent, Vega 1 and Vega 2, the instruments operated normally and yielded a vertical profile for the water vapor distribution in the night-side Venus atmosphere throughout the layer from 60-km altitude to 30-25 km. The landing sites of the two spacecraft were about 1500 km apart. Table II gives the preliminary results of the humidity measurements.

To arrive at a more detailed profile of the water

vapor distribution a thorough analysis of all the telemetered information will have to be made, taking into account the exact pressure and temperature readings along the descent tracks as well as the flight dynamics.

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<sup>2</sup>D. M. Hunten, L. Colin, T. M. Donahue, and V. I. Moroz, eds., *Venus* (Space Science Series), Univ. Arizona Press (1983).

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<sup>5</sup>Yu. A. Surkov, V. F. Ivanova, A. N. Pudov, V. A. Pavlenko, N. A. Davydov, and D. M. Sheinin, *Kosm. Issled.* **21**, 231 (1983) [*Cosmic Res.* **21**, 173 (1983)].

## Active spectrometry of the ultraviolet absorption within the Venus atmosphere

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The 2300-4000 Å absorption spectrum of the Venus atmosphere was measured aboard the *Vega 1, 2* landing modules by a stroboscopic xenon lamp and a 512-channel grating spectrometer, sampling a 170-cm optical path. A prominent broad absorption band, devoid of fine structure, shows a height-dependent profile suggesting that the principal absorbent may be the S<sub>8</sub> allotrope of sulfur in the gas phase, with mixing ratios of 25, 5 ppm at  $H = 45, 25$  km.

Spectrophotometric sounding was first utilized to study the Venus atmosphere in December 1978, on the Soviet *Venera 11* and *Venera 12* landing craft.<sup>1,2</sup> The landers carried an optical spectrometer which recorded the spectrum of scattered sunlight that had penetrated deep down into the atmosphere. Sequences of spectra were taken as the landers descended, and were analyzed to yield information on the abundance of some of the minor atmospheric constituents, the properties of the aerosol component, and the total amount of solar energy absorbed at various heights at the wavelengths of observation. In March 1982 an improved version of the optical spectrometer was successfully flown on the *Venera 13, 14* landers.<sup>3-5</sup>

The geometric considerations entailed in continuing the mission onward to Comet Halley made it necessary to land the *Vega 1* and *Vega 2* capsules on the planet's night side. Accordingly we proposed that the atmosphere be probed spectrophotometrically from these spacecraft by means of "active spectrometry": the spectrometer would have an artificial light source with optics enabling the light beam to pierce the ambient atmospheric gas. Such a design would of course be effective only in parts of the spectrum where the atmosphere has a large absorption

coefficient; for that reason we selected the 2300-4000 Å wavelength range.

Identical "ISAV" ultraviolet spectrometers were mounted on the *Vega 1* and *Vega 2* landers and measured the absorption produced in the 2300-4000 Å region by the gaseous constituents of the Venus atmosphere. Outside the frame of the landing module we attached a "cuvette" — a tube about 85 cm long (Fig. 1) through which the ambient gas would pass as propelled by the velocity pressure-head. Radiation from a pulsed stroboscopic lamp sealed inside the spacecraft housing passes through a lens (also sealed), enters the cuvette, which it transverses twice (a 170-cm path), experiencing some absorption by the atmospheric gases, and finally returns into the sealed part of the spacecraft, where the beam is fed to the analysis section of the spectrometer. Here a spectrum is formed by a concave holographic diffraction grating and is recorded by an array of 512 silicon photodiodes. The nominal wavelength resolution, corresponding to a single element of the array, is  $\Delta\lambda \approx 4$  Å, but aberration and justification errors impair this value threefold.

A complete spectrum, comprising all 512 elements from  $\lambda \approx 0.2$  to  $0.4 \mu$ , can be stored in the on-

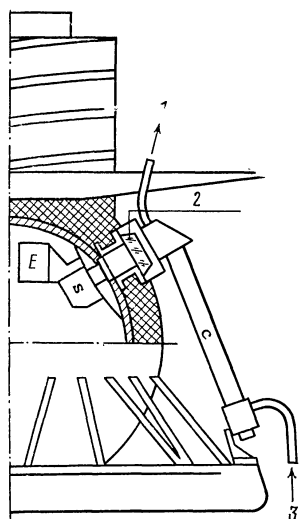


FIG. 1. Schematic diagram of the ultraviolet spectrometer aboard the Vega landers. C, cuvette tube; S, spectrum analysis section and stroboscopic lamp; E, electronics section. 1) Gas outlet; 2) lens illuminating cuvette; 3) gas inlet.

board memory in 60 sec at heights  $H > 25$  km above the Venus surface, and in 36 sec at  $H < 25$  km. Furthermore, every 4 sec a 16-element "scan" of the spectrum is formed, each element representing a numerical average of the signals from 32 consecutive diodes in the array.

On each Vega mission the spectrometer was turned on at the time of atmosphere entry, and it continued to function until touchdown. The information was telemetered to earth in compact code.

This instrument is distinctive for having optical components located both inside and outside the spacecraft. Thus certain portions of the lander (its casing, the illuminating lens, and so on) had to be considered in the overall optical design, and the spectrometer was therefore readjusted immediately after its separate sections were installed in the landing capsule. Subsequent deformations of the spacecraft walls disturbed the operation of the spectrometer.

At present the data are being processed as follows. As a reference spectrum  $E_0$ , in which absorption is assumed to be absent, we use the first spectrum acquired after Venus atmosphere entry. The spectrum  $Z$  observed upon landing is regarded as a "dark" spectrum, corresponding to total absorption. We then define the transmittance  $T$  of the gas for the remaining spectra  $E$  as the ratio

$$T = \frac{E - Z}{E_0 - Z}.$$

Empirical corrections are applied for the temperature variation of the diodes, using the signal at the shortest wavelengths, in the region where the lamp emits hardly any radiation. We also introduce an empirical correction for possible drift in the analysis-section parameters, adopting an integer  $C$  to describe how many elements a spectrum  $E$  may have shifted relative to the reference spectrum  $E_0$  during the descent. The best choice for  $C$  is indicated by noting the minima of features representing lines in the lamp spectrum; in this fashion we obtain a parameter  $C$

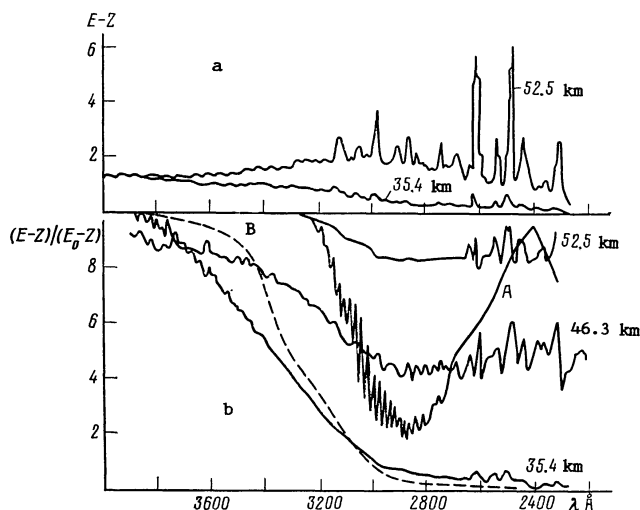


FIG. 2. Ultraviolet absorption recorded by the Vega 2 lander in the deep Venus atmosphere layers: a) the xenon-lamp emission spectrum ( $E - Z$ ; see the text) after traversing a 170-cm optical path in the atmosphere at the two heights indicated; b) the  $(E - Z)/(E_0 - Z)$  ratio (the residual fine structure in the curves is due to incomplete compensation for the relative  $\lambda$ -shift in the different spectra). Curve A represents a synthetic  $\text{SO}_2$  absorption spectrum, assuming 110 ppm at  $H = 35$  km; curve B, a synthetic  $\text{S}_8$  absorption spectrum (15 ppm at 35 km).

ranging from 0 at the start of the descent to 4-6 at the end.

The "scan" spectra are reduced by averaging them in pairs and subtracting the signal of the 16th ("dark") element from the signal of the first 15 elements in the scan spectrum.

On both missions the ISAV spectrometer functioned nominally from deployment to landing, with operating characteristics practically identical to those measured in tests on the ground. Each landing craft obtained about 30 full-resolution spectra, and another 450 scan spectra with low resolution. Apart from the abrupt fluctuations recorded during the first 60 sec due to the inertia load at atmosphere entry, the successive spectra exhibited a slight strengthening of the signal (by proportional amounts at all wavelengths) down to the  $\approx 55$ -km level, followed by a monotonic weakening as the lander continued to descend. At  $H \approx 10$  km the signal from the lamp disappeared completely, and the potentials at the outputs of the CCD array elements measured on the planetary surface were close to the dark level measured on the earth prior to the start of the mission.

Figure 2 illustrates some typical full-resolution spectra recorded by Vega 2 at various heights; the Vega 1 spectra are much the same. The most striking feature in these spectra is the broad absorption band, which first began to emerge at  $H \approx 55$  km. It deepens rapidly from 50 km down to 40 km; below that level it becomes somewhat shallower, or remains nearly constant.

When planning the experiment we assumed that the most important absorbing gas in this wavelength range would be sulfur dioxide. Curve A in Fig. 2 represents a synthetic spectrum calculated on this premise; one can easily see that its shape does not quite agree with the absorption band recorded experimentally. The absence of the band structure typical of  $\text{SO}_2$  implies that for the unknown absorbing gas

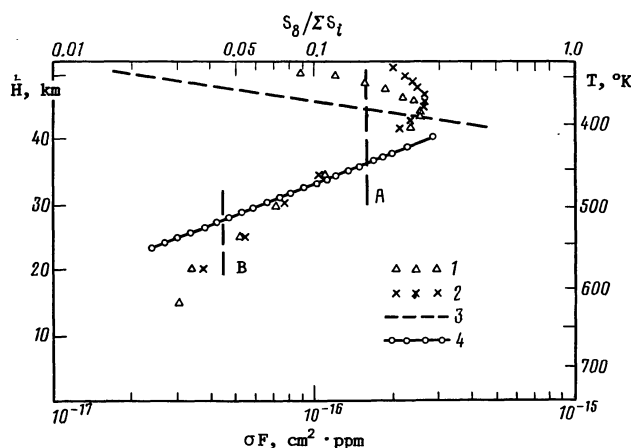


FIG. 3. Product  $\sigma F$  of the absorption cross section by the mixing ratio as a function of height  $H$  above the Venus surface for the group of diode elements centered at  $\lambda = 3070 \text{ \AA}$ . 1) Data from Vega 1 low-resolution spectra; 2) Vega 2 data; 3) the  $\sigma F$  line corresponding to sulfur saturation; 4) the  $S_8/\Sigma S_i$  fraction for small partial pressures of sulfur.<sup>12</sup> Line A, the  $\sigma F$  value for  $S_8$  at a mixing ratio  $F = 15 \text{ ppm}$ ; line B, the  $\sigma F$  value for  $SO_2$  at  $F = 110 \text{ ppm}$ .

which produced the observed band, the product of the absorption cross section  $\sigma$  [ $\text{cm}^2$ ] by the gas abundance is substantially greater than for  $SO_2$ .

However, the  $SO_2$  absorption cross section, for which the synthetic spectrum A was computed, refers to room temperature. (We have utilized a variety of published data, particularly those of Brasington.<sup>6</sup>) We now plan to make new measurements of the  $SO_2$  absorption spectrum at high temperatures. Some qualitative information on the behavior of the ultraviolet band at  $T \approx 470^\circ\text{K}$  is already available, and indicates that the  $SO_2$  band differs little in general character from what is found in the standard environment. Thus we still contend that the band observed in the absorption spectrum of the Venus atmosphere belongs to some other gas.

What this gas may be has not yet been fully decided. As a working hypothesis we have considered identifying it with allotropes of free sulfur ( $S_n$ ,  $2 < n < 8$ ) in the gaseous phase. At  $T = 455^\circ\text{K}$ , corresponding to  $H \approx 35 \text{ km}$ , much of the sulfur ought to be in the form of  $S_8$ . In Fig. 2 curve B is a synthetic spectrum calculated from  $S_8$  absorption cross sections measured both in the gas phase and in solution<sup>7</sup> (our own measurements have been used as well). Notice that, in an approximate sense,  $S_8$  can indeed reproduce the absorption profile observed, although a significant disparity remains in the 3300–3800  $\text{\AA}$  region.

Very little information is available on the UV absorption spectra of other allotropic forms of sulfur. The  $S_3$ ,  $S_4$  spectra<sup>8</sup> differ strongly from what was observed on Venus. Hardly anything is known about the  $S_5$ ,  $S_6$ ,  $S_7$  spectra. In the  $S_2$  absorption spectrum<sup>8</sup> fine structure is evident, but none is shown by our observations. New laboratory studies are currently being made to improve our knowledge of the spectroscopic properties of free sulfur.

Sulfuric acid is prominent among the cloud-layer particles, so one would expect its vapor to occur at the 30–35 km levels in relatively high abundance ( $\approx 100 \text{ ppm}$ ; see, for example, Craig et al.<sup>9</sup>), and it is worthwhile comparing the absorption spectrum of

$H_2SO_4$  absorption spectrum at  $T \approx 420^\circ\text{K}$ . The results suggest that sulfuric acid vapor would contribute only a small amount to the absorption observed by the Vega landers.

Many other molecules besides sulfur have been considered as candidates for identification. Among these only the sulfanes  $H_2S_n$  ( $n \geq 2$ ) and the chlor-sulfanes  $SnCl_m$  have spectra resembling those observed, but these compounds would probably be unstable in the Venus atmosphere.

If  $S_8$  does dominate the absorption at  $\lambda \approx 3000 \text{ \AA}$ , its abundance should be quite high, ranging from 5 ppm at  $H \approx 25 \text{ km}$  to 25 ppm at 45 km. Such values would be two orders higher than hitherto inferred from indirect evidence based on spectrometry at longer wavelengths.<sup>10, 11</sup>

In attempting to identify the absorbing gas one should consider not only its spectral properties but also its thermodynamic characteristics. Indeed  $S_8$  is more or less compatible with the latter criterion. Whatever the absorbing gas may be, the product of the absorption cross section  $\sigma$  by the mixing ratio  $F$  will have the value

$$\sigma F = \frac{10^6 \ln(I/I_0)}{LN} \text{ cm}^2 \cdot \text{ppm}$$

where  $I$ ,  $I_0$  denote the intensities in the presence and in the absence of the absorbing gas,  $L$  is the optical path length, and  $N$  is the total number density [ $\text{cm}^{-3}$ ]. In Fig. 3 we have plotted the  $\sigma F$  height profiles for the two Vega landers, as derived from the low-resolution scan spectra at  $\lambda = 3070 \text{ \AA}$ . Also shown in this diagram are the corresponding sulfur saturation line and a line expressing the fraction of  $S_8$  relative to all the sulfur allotropes combined. On comparing all these curves we see that the observed  $\sigma F$  height profile does roughly conform to the constraints which condensation and thermodynamic equilibrium impose among the sulfur allotropes, although even in this respect the agreement is imperfect (the condensation line runs somewhat below the measured curves).

Our analysis of the experimental results is only in its beginning stages, however, and other possible identifications may well emerge.

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<sup>8</sup>B. Meyer, T. V. Oomen and D. Jensen, *J. Phys. Chem.* **75**, 912 (1971).



<sup>9</sup>R. A. Craig, R. T. Reynolds, B. Ragent, G. C. Carle, F. Woeller, and J. B. Pollack, *Icarus* **53**, 1 (1983).

<sup>10</sup>N. F. San'ko, *Kosm. Issled.* **18**, 600 (1980) [*Cosmic Res.* **18**, 437 (1981)].

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<sup>12</sup>K. C. Mills, *Thermodynamic Data for Inorganic Sulphides, Selenides, and Tellurides*, Butterworth, London (1974).

## Vega 1, 2 optical spectrometry of Venus atmospheric aerosols at the 60–30 km levels: preliminary results

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Spectrometer measurements of the aerosol particle-density profiles above the *Vega* 1, 2 landing sites generally confirm the height-zone structure found in earlier sounding of the Venus atmosphere: a three-layer main cloud deck, an intermediate zone, and a subcloud haze region. However, the *Vega* results show substantial differences in the number density and especially the size spectrum of the aerosols. A tropospheric nightglow is present at  $\lambda \approx 1 \mu$ . The backscatter and extinction coefficients undergo relatively little variation over the 63–32 km height range. Submicron atmospheric particles appear to be abundant above the landing sites.

The identical ISAV-A spectrometers aboard the *Vega* 1 and *Vega* 2 landers were designed for investigating the aerosol content of the clouds on Venus. Along each flight trajectory the instrument would measure the number density of aerosol particles as well as their size spectrum and refractive index; it would provide information on the particle shape and on the backscatter coefficient. Only once before has the particle size spectrum been determined in situ in the Venus clouds: with the Pioneer Venus Large Probe,<sup>1,2</sup> in December 1978.

### 1. MEASUREMENT TECHNIQUE

Each ISAV-A aerosol analyzer consists of two functional components, a photoelectric aerosol spectrometer and a backscatter sensor. The aerosol spectrometer operates by measuring the light beams that individual particles passing through the instrument scatter in four different directions. The backscatter sensor measures light scattered by a certain batch of aerosol medium located near the instrument, and/or the intrinsic emission of the atmosphere.

In the schematic drawing of Fig. 1, light from the 5-W incandescent halogen lamp 1 is focused by the set of mirrors 2 onto a "sampling region" in which the light scattered by any aerosol particles will be measured. This region has a  $\approx 1\text{-mm}^3$  volume. Portions of the incident light scattered forward, backward, and laterally (by scattering angles of  $7^\circ$ – $17^\circ$ ,  $165^\circ$ – $175^\circ$ ,  $25^\circ$ – $65^\circ$ , respectively) are received by the four electrooptical devices 3–6, which use silicon cascade photodiodes as detectors. The two lateral sensors operate at the same scattering angles but in different azimuths.

The backscatter sensor is housed in the same box as the aerosol spectrometer. Light from the lamp 1 is sent by the reflector 7 out through the window 8 into the free atmosphere. Some of that light, scattered backward in the atmosphere by angles of  $160^\circ$ – $175^\circ$ , will reenter the instrument through the window 9 and strike the electro-optical detector 10. The backscatter sensor itself has a  $5\text{-cm}^3$  effective

working volume and is centered  $\approx 3$  cm away from the window. From time to time the lamp 1 is switched off; the backscatter sensor will then record only background radiation entering the outside, thereby acting as a photometer.

All the photodetectors are stowed along with the attendant electronics in the sealed part of the sensor compartment, which in turn is mounted on the landing ring frame; the optics are in the unsealed part of the same compartment, and the signal processing takes place in electronic systems inside the descent capsule.

As an aerosol particle flies through the spectrometer, the maximum logarithmic strengths of the pulses generated at the four photodiode outputs are recorded in the on-board memory and held there until the next particle goes through. Twice in each telemetry frame (0.43 sec) the spectrometer is interrogated by the lander systems, and each time the amplitudes of the four pulses, which serve to describe the scattering diagram of an individual particle, are transmitted to earth.

Provision is made in the ISAV-A for a 64-channel pulse-height analyzer, whose input receives in logarithmic form all the pulses from one of the lateral-scatter photodiodes. This analyzer acts to determine the size spectrum of all the particles that pass through the instrument during the 27-sec integration time, the interval at which the content of the analyzer cells is telemetered to earth. The instrument has a dynamic range of  $10^4$  in the pulse amplitude.

On descent of the landing craft, the oncoming gas flow propels aerosol particles into the sampling region through a suction device (Fig. 1), which comprises an entry nozzle 11 pointing downward, coaxial with a delivery tube 12 connected to an outlet pipe 13, as well as a capillary 14. To produce aerodynamic focusing, purified gas from the ambient atmosphere is supplied through the side tube 15 and the aerosol filter 16.