Reports

Clouds of Venus: Evidence for Their Nature

Abstract. *The linear polarization of sunlight multiply scattered by the atmosphere and cloud particles of Venus has been computed and compared with observations over the wavelength range from the ultraviolet to the infrared region. The following properties of the visible cloud layer are derived: the refractive index of the cloud particles is 1.45 ± 0.02 at a wavelength of 0.55 micron, and there is an indication of a slight decrease in the value from the ultraviolet to the near-infrared region; the mean particle radius is very near 1 micron, and most of the particles are spherical; the cloud layer occurs high in the atmosphere where the pressure is about 50 millibars (equivalent to an altitude of approximately 20 kilometers on the earth). The results for the index of refraction eliminate the possibility that the visible clouds are composed of pure water or ice.*

The polarization of sunlight reflected by Venus was first measured by Lyot (*1*) in 1922. The amount of polarization observed was small (Fig. 1), but, because of the high accuracy of the measurements and the sensitivity of the polarization to the optical properties of the scattering medium, the observations contain a large amount of information. Coffeen and Gehrels (*2*) extended the measurements to several wavelengths from the near-ultraviolet region ($\lambda = 0.34\ \mu$) to the near-infrared region ($\lambda = 0.99\ \mu$).

The fact that the mass of the Venus atmosphere is large ($p \sim 100$ atm) (*3*) assures that the polarization observations refer primarily to photons multiply scattered within the atmosphere and not to reflections from a solid planetary surface. A complete theoretical interpretation of the observations must, therefore, be based on solutions of the radiative transfer equation, which takes multiple scattering into account. Exact solutions for a Rayleigh atmosphere (gaseous molecules or particles with radius $r \ll \lambda$) have been obtained by Chandrasekhar (*4*), but, as shown in Fig. 1, Rayleigh scattering produces a polarization at visible wavelengths that is much larger than the polarization observed on Venus.

Laboratory measurements, as well as theoretical calculations for single scattering by spherical particles, indicate that the polarization of Venus is characteristic of scattering by particles with $r \sim \lambda$. Using his laboratory measurements, Lyot (*1*) estimated that clouds composed of water drops (refractive index $n_r \sim 1.33$) with $r \sim 1.25\ \mu$ would be in agreement with his observations of Venus. Coffeen (*5*), on the other hand, compared the observations of Coffeen and Gehrels (*2*) with calculations for single scattering by spheres and concluded that $1.43 \leqslant n_r \leqslant 1.55$ and $r \sim 1.25\ \mu$.

We have obtained numerical solutions to the exact equations for the multiple scattering of light (including polarization) from a plane parallel atmosphere consisting of a mixture of spherical particles and a Rayleigh gas (*6*). The results are integrated over the visible part of the planetary disk to allow a comparison with the observations of Venus. The multiple scattering calculations depend upon the phase matrix for single scattering, which may be calculated from the Mie theory. The phase matrix, in turn, depends upon the real refractive index (*7*) and the particle size distribution (*8*). The calculations were found to be sensitive to the mean particle radius and to the dispersion about the mean radius, but insensitive to higher moments of the size distribution. For the results presented below, the dispersion of particle size about the mean radius was adjusted to give close agreement with the observed polarization. Hence, the results, which are presented in Figs. 2 to 4, showing polarization as a function of the planet's phase angle, depend upon two parameters: the index of refraction, n_r, and the mean particle ra-

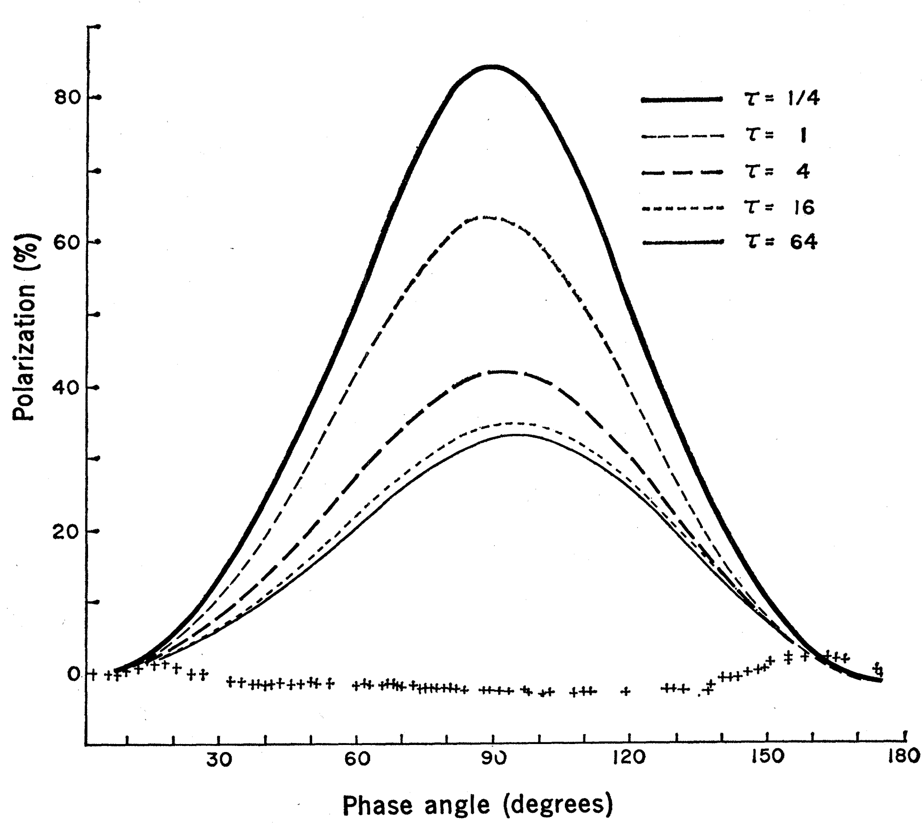

Fig. 1. The pluses represent Lyot's measurements of the polarization of the visual light reflected by Venus (*1*). The theoretical curves are for Rayleigh atmospheres of different thicknesses.

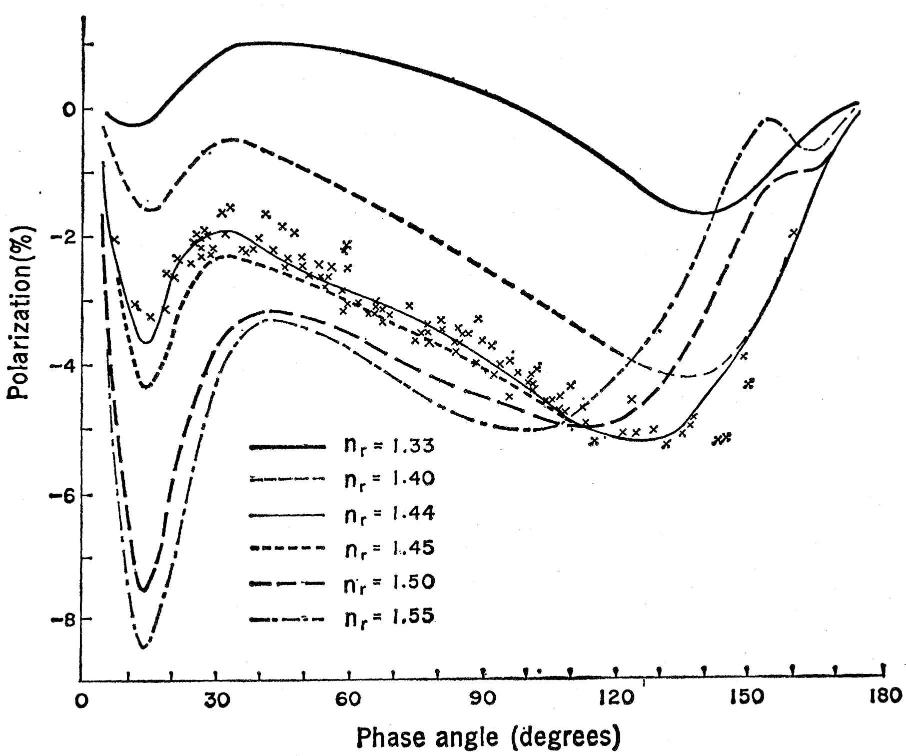

Fig. 2. The crosses show the observations of Coffeen and Gehrels of the polarization of Venus at a wavelength of 0.99 μ (*2*). For each refractive index n_r the theoretical calculations are for the particle size giving best agreement with the observations: $\bar{r} = 0.6$, 0.8, 1.1, 1.1, 1.2, and 1.2 μ, respectively, beginning with $n_r = 1.33$. The curves for $n_r = 1.44$ and 1.45 are indistinguishable for phase angles greater than 110°. The albedo of Venus is assumed to be $\sim$ 90 percent at $\lambda = 0.99$ μ.

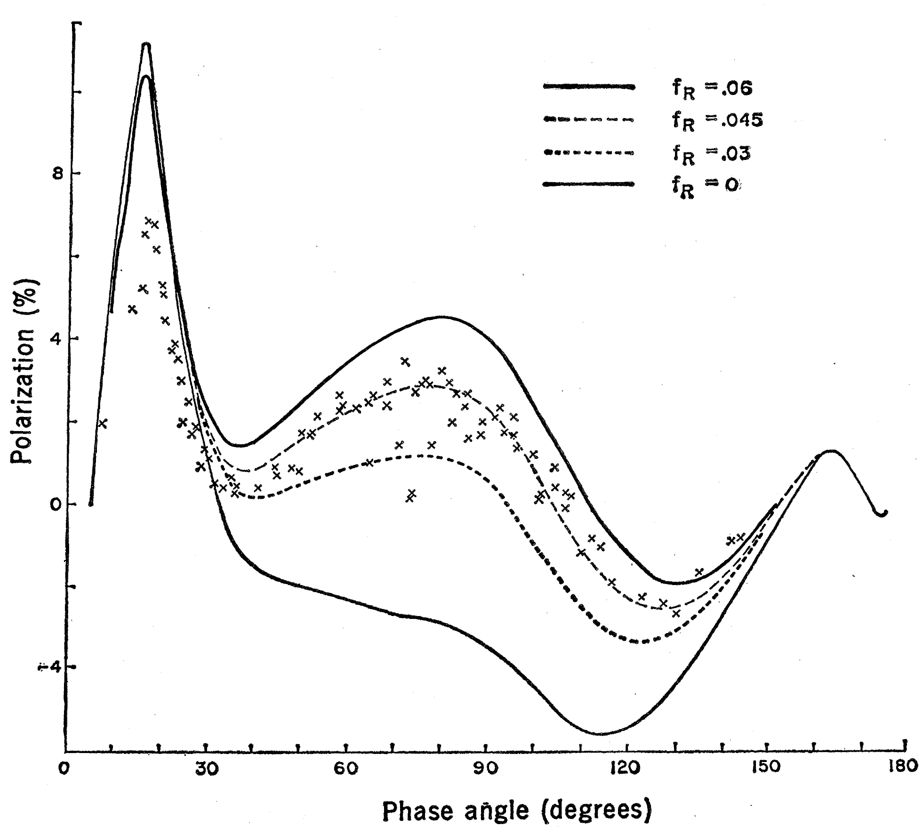

Fig. 3. The crosses show the observations of Coffeen and Gehrels at $\lambda = 0.365$ μ (*2*). The theoretical curves are computed with a fraction f_R of the phase matrix being Rayleigh scattering and a fraction $(1 - f_R)$ being the Mie phase matrix for $n_r = 1.46$ and $\bar{r} = 1.1$ μ. The albedo of the planet is assumed to be $\sim$ 55 percent.

dius, $\bar{r}$. For observations at short wavelengths, where Rayleigh scattering is important because of its $1/\lambda^4$ dependence, the fractional contribution of Rayleigh scattering was an additional parameter.

The sensitivity of the theoretical computations to changes in the refractive index is illustrated by Fig. 2 which includes Coffeen and Gehrels' observations at $\lambda = 0.99$ μ. For each refractive index that particle size is shown that gives the best overall agreement for all wavelengths from 0.34 to 0.99 μ. The minimum near a phase angle of 15° is the glory, which arises from surface waves generated on spherical particles by edge rays; the glory is very broad at this wavelength because of the small size parameter $x = 2\pi\bar{r}/\lambda$. The broad maximum near a phase angle of 30° is the primary rainbow, which arises from rays internally reflected once in spherical particles; this feature becomes increasingly distinct toward shorter wavelengths.

At visual and shorter wavelengths there is a nonnegligible contribution from Rayleigh scattering, which may be estimated best from the ultraviolet observations. Figure 3 shows the results of calculations at $\lambda = 0.365$ μ for a model with a uniform mixture of spherical cloud particles and Rayleigh scatterers (*9*). The derived amount of Rayleigh scattering may then be used to obtain the pressure at a level of significant optical depth ($\tau \sim 1$) in the clouds (*5*, *10*); the result is $\sim$ 50 mb, which, for comparison, corresponds to the pressure in the earth's stratosphere at $\sim$ 20 km.

The visual observations of Lyot and the intermediate-bandwidth observations of Coffeen and Gehrels at $\lambda = 0.55$ μ are shown in Fig. 4. The theoretical curves illustrate the sensitivity of the polarization to variations in the particle size, and they indicate that the mean particle radius is ~ 1.1 μ. The agreement is closer with the intermediate-bandwidth observations of Coffeen and Gehrels than with the broad-bandwidth observations of Lyot; this result is not surprising since the calculations are monochromatic. The discrepancy with Lyot's observations for phase angles greater than 150° may not be too significant because the observations are least certain there and because the accuracy of the plane parallel approximation at large phase angles has not yet been determined. However, the discrepancy would be reduced with a narrower distribution of particle sizes, and it is significant that this positive polarization feature would be lost from the theoretical curves for broad size distributions.

A study of all of our results shows that the best fit to the observations occurs with a refractive index which decreases from ~ 1.46 in the ultraviolet region to ~ 1.43 at $\lambda = 0.99\ \mu$; the uncertainty in n_r is 0.02 at each wavelength (*11*). The mean particle radius is $1.1 \pm 0.1\ \mu$. Most of the particles must be spherical: the glory and rainbow are predicted for spheres but they are not expected for irregular particles. It cannot be argued that irregular particles might appear "fuzzy," and hence nearly spherical, for wavelengths $\lambda \sim r$ because the rainbow becomes increasingly sharp for shorter λ, as sharp as predicted for spherical particles. The dispersion in particle sizes in a unit volume and over the whole planet (within the upper cloud layer) is amazingly small; this result is unexpected for dust, but it is not unusual for a liquid in which condensation-evaporation is the primary determinant of particle size. The particle shape and the dispersion of particle sizes taken together strongly suggest that the cloud particles are liquid.

It should be emphasized that the cloud properties derived from the polarization refer to the top part of the clouds. Intensity measurements, for example, of absorption lines, include information on deeper layers where the cloud particle properties *may* differ and the pressure is certainly greater. This must also be borne in mind when one considers the color and spectral reflectivity of Venus. Nevertheless, the "polarization clouds" must be equated with the "visible clouds" of Venus; the "polarization clouds" have a significant optical depth on a planet-wide basis. The fact that these clouds have a substantial optical thickness high in the atmosphere, where $p \lesssim 50$ mb, only makes them all the more puzzling. It should also be emphasized that the visible clouds are composed of particles with a single refractive index (note, for example, the sharp rainbow in the ultraviolet); they *cannot* be composed of a mixture such as dust and water.

The above results stringently narrow the list of possible materials composing the visible clouds of Venus; indeed, most of the materials that have been proposed may be ruled out. The polarization data are incompatible with solid particulates such as SiO_2, NaCl, NH_4Cl, and $FeCl_2$ on several grounds, including their refractive indices. The refractive indices for pure water (H_2O) and ice are much too small, whereas the refractive indices for Hg and Hg compounds are much too large. Of course, the polarization results do not rule out the possible existence of these materials in some cloud deck beneath the visible clouds.

There are some cloud particle materials that have been discussed in the literature but that have uncertain refractive indices. Lewis (*12*), using the observed abundances of HCl and H_2O, predicted that cloud particles composed of an aqueous solution of hydrochloric acid ($HCl–H_2O$), with ~ 25 percent HCl by weight, should exist at the ~ 50 mb level if the temperature in this region is as low as 205°K. The Mariner 5 results are uncertain at this altitude but are not necessarily inconsistent with temperatures this low (*13*); theoretical models (*14*) predict temperatures on this order. The refractive index of $HCl–H_2O$ is 1.39 for an HCl concentration of 25 percent at 291°K and $\lambda = 0.589\ \mu$ (*15*); the refractive index does not increase significantly for the lower temperatures expected in the Venus clouds (*16*). On the basis of presently available data, it appears that clouds composed of $HCl–H_2O$ are not in agreement with the polarization results.

Carbon suboxide (C_3O_2), which has been proposed as a cloud particle material (*17*), has a refractive index of 1.454 at $\lambda = 0.589\ \mu$ for a temperature of 273°K (*18*), and hence it is not clear whether or not C_3O_2 has an acceptable value at $T = 200°$ to 240°K. However, the primary difficulty with C_3O_2 is the spectroscopic upper limit on the abundance of its vapor (*19*), which is a few orders of magnitude less than the amount required in the stratosphere of Venus for equilibrium with the condensate of the monomer. Although the low polymers of C_3O_2 have a lower vapor pressure and

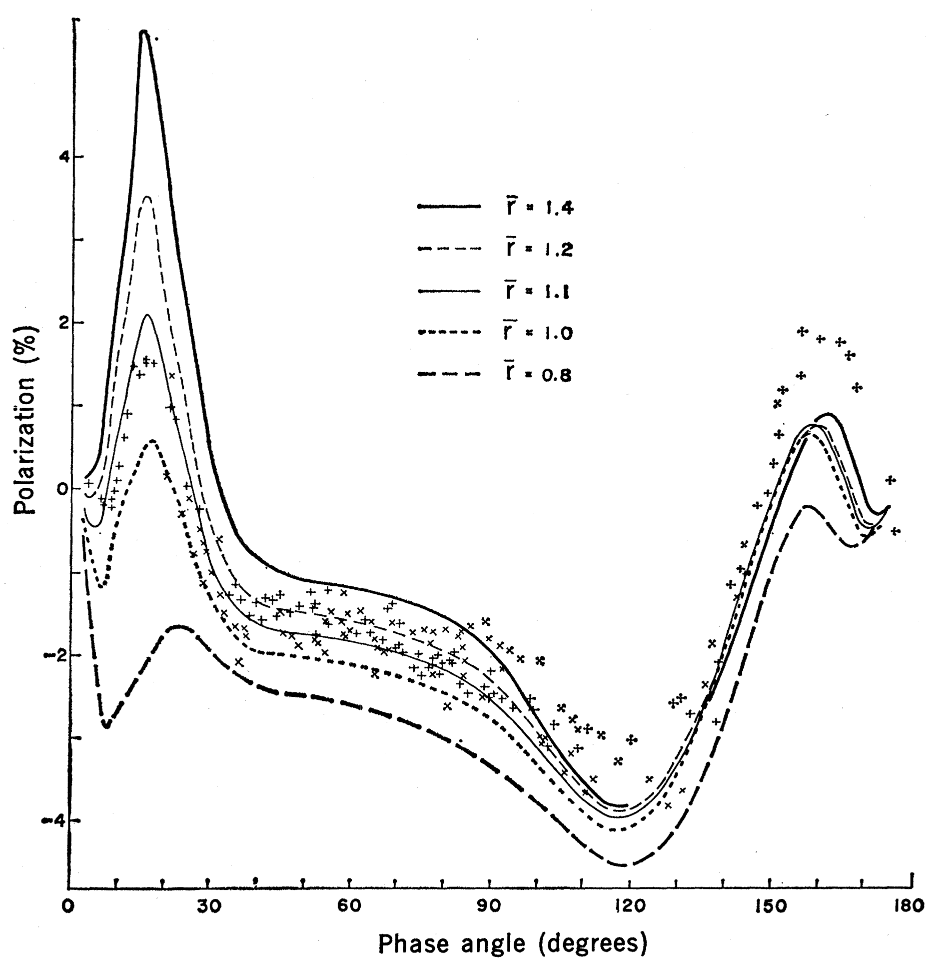

Fig. 4. The pluses represent the visual observations of Lyot (*1*), and the crosses are the intermediate-bandwidth observations of Coffeen and Gehrels at $\lambda = 0.55\ \mu$ (*2*). The theoretical curves are for $n_r = 1.45$ with several values for the mean radius $\bar{r}$. The albedo of Venus is assumed to be ~ 87 percent, and the Rayleigh scattering determined in the ultraviolet region ($f_R = 0.045$) is included after reduction by a λ^{-4} law.

are yellowish like Venus, there are many unanswered questions about the substance (Are the low polymers liquid? Is their vapor pressure low enough for the gas to go undetected? What is the refractive index? Are the low polymers stable at the expected temperatures and pressures? Are sufficient production rates plausible?). Carbon suboxide is hence a very uncertain material, but laboratory studies of it would be useful.

It is conceivable that water of hydration could reduce the refractive index of some minerals to $n_r \sim 1.45$ (*20*) or that dissolved salts may raise the refractive index of water sufficiently. However, such possibilities are very speculative without independent evidence for a particular material.

In summary, the comparison of polarization observations with theoretical calculations has accurately yielded the optical properties of the visible clouds of Venus. These properties rule out most of the materials that have been suggested for these clouds, including water and ice. An aqueous solution of hydrochloric acid (HCl–H_2O) and carbon suboxide (C_3O_2) are not absolutely excluded, but the likelihood for either is not high. A new look at the question of the Venus cloud composition seems in order.

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6. The calculations were based primarily on the doubling method which has been described in the case in which polarization is neglected by H. C. van de Hulst ["A New Look at Multiple Scattering," *Nat. Aeronaut. Space Admin. Inst. Space Studies Rep.* (1963)] and by J. E. Hansen [*Astrophys. J.* **155**, 565 (1969)]. The extension of the method to include polarization is described by J. E. Hansen [*J. Atmos. Sci.* **28**, 120 (1971)] and by J. E. Hansen and J. W. Hovenier [*J. Quant. Spectrosc. Radiat. Transfer*, in press]. More detailed results for Venus will be published elsewhere.
7. The imaginary part of the refractive index must be very small for the particles in the upper cloud layer on Venus, and the single particle albedo, ω_0, must be close to unity. Since the spherical albedo of Venus is less than 100 percent at each wavelength of interest, we may choose either (i) a finite optical thickness with a partially absorbing ground, (ii) some interparticle gaseous absorption, (iii) a small absorption within the particle, or some combination of (i), (ii), and (iii). However, we found the differences in the resulting polarization under these assumptions to be negligible, and the calculations for the figures in this report were made on the basis of assumption (iii).
8. The effect of the particle size distribution may be described by a small number of parameters. For the amount of detail that may be extracted from the presently available observations of Venus, two parameters are sufficient: the mean scattering radius, $\bar{r}$, which is the mean radius with the particle scattering cross section included as a weight factor, and the dispersion of particle sizes, $\bar{r}^2$, which is the second moment about the mean, again with the cross section included as a weight factor. Results shown in Figs. 2–4 were obtained with the gamma function size distribution
$$n(r) \propto r^{-p_2} \exp(-rp_2/p_1)$$
with $p_2 = 6$, which corresponds to a moderate dispersion; p_1, the mode radius, was allowed to vary to obtain different values for the mean radius.
9. The phase variation of line strengths [J. W. Chamberlain and G. R. Smith, *Astrophys. J.* **160**, 755 (1970); L. D. Gray Young, R. A. Schorn, E. S. Barker, M. MacFarlane, *Icarus* **11**, 390 (1969)] and several estimates of a long mean free path in the cloud layer [R. Goody, *Planet. Space Sci.* **15**, 1817 (1967); M. J. S. Belton, D. M. Hunten, R. M. Goody, in *The Atmospheres of Venus and Mars*, J. C. Brandt and M. B. McElroy, Eds. (Gordon & Breach, New York, 1968); J. E. Hansen, *Astrophys. J.* **158**, 337 (1969)] indicate that the assumption of uniform mixing is probably better than the often used hypothesis of a dense "reflecting layer" cloud with a gas above. The mixed model may be less valid for polarizations than for intensities, but the particle size, shape, and refractive index which we derive are independent of this assumption and the derived pressure does not depend greatly on it either.
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11. Despite the small magnitude of the variation in n_r with λ, the variation is significant. Any model (with a given size distribution and refractive index, including a possible dispersion in n_r) must have a larger refractive index in the ultraviolet than in the infrared region in order to obtain agreement in both wavelength regions.
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21. We thank S. I. Rasool and R. Jastrow for their suggestions, and D. L. Coffeen, J. W. Hovenier, J. Lewis, W. Plummer, and H. C. van de Hulst for informative discussions. During the course of this work, J. Hansen was supported consecutively by a National Academy of Sciences–National Research Council research associateship supported by NASA at the Institute for Space Studies; an NSF fellowship at the Sterrewacht, Leiden, Netherlands; and NASA grant 33-008-012 through Columbia University.

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Microbial Degradation of Organic Matter in the Deep Sea

Abstract. *Food materials from the sunken and recovered research submarine* Alvin *were found to be in a strikingly well-preserved state after exposure for more than 10 months to deep-sea conditions. Subsequent experiments substantiated this observation and indicated that rates of microbial degradation were 10 to 100 times slower in the deep sea than in controls under comparable temperatures.*

On 16 October 1968, the research submersible *Alvin* of the Woods Hole Oceanographic Institution sank in about 1540 m of water, 135 miles southeast of Woods Hole, Massachusetts. The accident occurred when, because of a broken cable, the vessel dropped into the sea with an open hatch and sank after the crew of three escaped safely. A photograph taken on 13 June 1969 by U.S.N.S. *Mizar* prior to the retrieval operations showed the position of the vessel on the sea floor, the hatch still being open (Fig. 1). On 1 September 1969, *Alvin* was brought to the surface (*1*). Among the items recovered was the crew's lunch consisting of two thermos bottles filled with bouillon and a plastic box containing sandwiches and apples. From general appearance, taste, smell, consistency, and preliminary bacteriological and biochemical assays, these food materials were strikingly well-preserved. When kept under refrigeration at 3°C, the starchy and proteinaceous materials spoiled in a few weeks.

Possible implications of this unexpected finding led us to make some additional observations. The environmental conditions at a depth of 1500