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COMMENTS ON THE PAPER BY D.G. REA AND B.T. O'LEARY ON THE COMPOSITION OF THE VENUS CLOUDS

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In a recent paper Rea and O'Leary (1968) examined the cases for and against ice clouds on Venus and concluded ".... that there is no direct evidence for H_2O ice crystals, and furthermore, if they do exist on Venus and dominate the near-infrared scattering process, they must be submicron in diameter." We believe that at least the latter of these two conclusions is not correct, because clouds composed of ice particles a few microns in diameter do not generally cause absorption features at 1.5 and 2.0μ as strong as assumed by Rea and O'Leary. Their conclusion was based in part on laboratory reflectivity spectra obtained by Zander (1966) but we believe that Zander's reflectivity spectra are representative of particles an order of magnitude larger than suggested in Zander's publication.

Rea and O'Leary examined spectra of Venus obtained by Kuiper (1962) with an earth-based telescope for wavelengths $1.4\mu \leq \lambda \leq 2.3\mu$ and balloon observations of Bottema, Plummer, Strong, and Zander (1964, 1965) for $1.8\mu \lesssim \lambda \lesssim 3.4\mu$. They showed that the absorption near 1.5 and 2.0μ is due largely to CO_2; hence, except for the reflectivity minimum near 3μ, there is no significant evidence for the broad band absorption features that would be expected for ice in the near-infrared.

Rea and O'Leary illustrated spectral reflectivities of ice clouds having particle diameters $\sim$ 10-100μ and these showed very strong absorption features at 1.5 and 2.0μ. Although the strength of these features would diminish for smaller particles, it was shown that the features were nearly as strong in laboratory measurements by Zander (1966) in which the particles were reported as having diameters primarily in the range $1\mu \leq d \leq 3\mu$. From this they argued that either ice particles are not the principal scatterers of the infrared radiation on Venus, or, if they are, the particle diameters must be less than 1μ and probably less than .1μ. Since the planet-wide existence of submicron ice particles is unlikely they concluded that the major scatterers of radiation on Venus are almost certainly not composed of H_2O ice.

However, solutions of the radiative transfer problem for diffuse reflection from ice clouds have been made (Hansen and Cheyney, 1968) for a size distribution of spherical particles and compared to Zander's observations. The optical constants for ice were taken from the tables compiled by Irvine and Pollack (1968); from these the absorption and scattering cross sections and the phase function were calculated for each particle, weighted for the mixture, and employed in the transfer problem to obtain the complete angular distribution of reflected light. When the size distribution specified in Zander's (1966) article (diameters of 1-3μ) was employed, the absorption features at 1.5 and 2.0μ were found to be much too weak to be compatible with the laboratory observations; however, it was learned from Zander (1968) that a significant number of the 1-3μ particles were clustered into tightly packed (void space $\lesssim$ 20%) aggregates as large as 15μ. Since the components of an aggregate do not scatter incoherently it is a better approximation to treat each aggregate as a single large particle, and a relatively small number of these may completely change the scattering properties of a unit volume. According to Zander (1968) $\sim$ 20% of the particles were aggregates (with an aggregate counted as being one particle) and the distribution of the aggregates peaked at d $\sim$ 10μ. When the complete distribution including aggregates was used in the radiative transfer problem a close fit was obtained with Zander's observed curve.

From the apparent discrepancy between Sagan and Pollack's (1967) calculations and Zander's laboratory spectra, Rea and O'Leary suggested that Sagan and Pollack's approximate radiative transfer solution may be in serious error, but our results for a narrow size distribution are compatible with the single particle calculations of Sagan and Pollack. Certainly their two stream approximation can not cause an order of magnitude error in the particle sizing.

The primary point that we wish to make is that with micron sized ice particles as the major scatterers the reflectivity minima near 1.5 and 2.0μ are not generally as large as assumed by Rea and O'Leary and hence Kuiper's ground based observations may be compatible with clouds of such particles. For example, with a particle size distribution having diameters $1\mu \leq d \leq 3\mu$ with the maximum of the distribution at 1.7μ we obtain the reflectivities in Table 1

Table 1

	λ(μ)								
λ →	1.52	1.7	1.85	2.0	2.15	3.0	3.2	3.4	Spherical Albedo at λ = 1.85μ
τ = 8	.25	.24	.23	.18	.18	.003	.02	.13	40%
τ = 16	.45	.46	.45	.35	.37	.003	.02	.14	56%
τ = 32	.60	.67	.68	.47	.55	.003	.02	.14	70%

where the reflectivity is the ratio of the calculated intensity to the intensity of a Lambert surface with albedo unity and τ is the optical thickness of the ice clouds at $\lambda = .95\mu$. The computations were made for the angles of incidence and emergence in Zander's experiment and hence the results are not identical to the integrated light from Venus at a given phase angle, but Rea and O'Leary's conclusions were also based on Zander's experiment. The table illustrates that with a finite cloud of micron-sized ice particles the absorption features at 1.5 and 2.0μ are weak and hence the spectroscopic observations must be accurate in order to establish or rule out the existence of ice clouds.

We do not maintain that this represents positive evidence for ice clouds on Venus; we do believe, however, that the arguments against having clouds of micron-sized ice crystals are not yet conclusive.

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