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COMMENTS ON THE DETECTION OF WATER AND ICE CLOUDS ON VENUS

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Because of circumstances, I have been unable to prepare an adequate discussion of the recent observations described by Dr. Strong. Instead I propose to comment on the detection of Venusian clouds, particularly the problems of interpretation of the data, and to suggest some additional observations that may help clarify the nature of the clouds without recourse to actual sampling.

By now it is generally agreed, I believe, that the Venusian atmosphere contains large amounts of particulate matter that appears to be in permanent suspension. This material must certainly be related to the observed planetary brightness, polarization, and spectrum, not only in the ultraviolet, visible, and infrared region, but in the near microwave region as well.

Two years ago in Liège (Ref. 1), I proposed that this particulate matter could very well be composed of the condensation products of water substance. In a subsequent article (Ref. 2) I elaborated on several lines of reasoning in support of this hypothesis, which I advanced in the face of the then current arguments favoring a rather dry atmosphere based on the near-infrared spectra of the planet, and prior to the announcement by J. Strong and co-authors (Ref. 3) of their balloon detection of the λ 1.13 μ H_2O bands.

The more recent balloon detection, also by Strong and his collaborators (Ref. 4), of ice particles in the upper atmosphere of Venus indicates the existence of at least two phases of water substance in the atmosphere of the planet. The spectroscopic detection of ice particles appears to be the only *direct* observational evidence of this kind, ever since B. Lyot's (Ref. 5) nearly 40-year-old analysis of the polarization curve in terms of water cloud droplets. If we accept the more recent evidence, the question still remains: how much water is there in the form of vapor and condensation products below the "visible" surface? I assert that this is still very much an open question.

First, let us take at face value the estimate of about 10 mg of water vapor per cm^2 above the "top" of the clouds, assumed to be around 100 mb, according to the analysis of the λ 1.13 μ observation (Ref. 3). This spectral region seems to be a good choice for the *vapor* detection since liquid water and ice show no strong absorption bands there. We then observe that the 100-mb pressure level is found at a height of about 16 km on Earth, somewhere between the levels of formation of high cirrus clouds and mother-of-pearl clouds. The deduced Venusian water vapor mixing ratios are actually ***higher*** than those observed for the terrestrial stratosphere above 12 km! On this basis alone, one might surmise that the amounts of atmospheric water substance on Venus and Earth are comparable. However, we note that Chamberlain (Ref. 6), has pointed out some serious uncertainties regarding the level of formation of the λ [illegible] μ bands.

Next let us consider the evidence for the existence of ice clouds on Venus. The Johns Hopkins group (Refs. 4, 7) base their deduction mainly on a comparison of the infrared spectrum of ice clouds produced in their laboratory with those of Venus. They have not published details on the laboratory experiment.[1] From our knowledge of the extreme difficulties in reproducing high cirrus cloud particles in the laboratory, and the fact that the infrared optical constants of ice are known only for bulk ice, we have to qualify this kind of experimental evidence. On the other hand, a theoretical prediction of the spectrum of diffusely reflected infrared sunlight on a cloud of nonspherical ice crystals of unknown shape, size, and size distribution is even more difficult. The best kind of test at present would therefore be a comparison with directly observed spectra of actual terrestrial ice clouds under similar conditions. Fortunately, this kind of evidence has just become available.

I refer to sunlit cloud spectra taken from a high-flying aircraft over terrestrial cloud systems, a kind of observation that has only recently been carried out, despite the evident need for it. The results are so far available only in the form of an unclassified report[2] by H. H. Blau and R[illegible] Espinola (Ref. 8). The work appears to have been carefully conducted, with infrared spectra obtained with resolution as high as, or higher than, those of the balloon instrument, and the well calibrated spectra are given in absolute units and for specified angles of illumination and observation. The most interesting results, for our purposes, are the average of eight spectra of dense cirrus clouds (Ref. 8, p. 102). These are uncorrected for path absorption and solar energy density. To compare them with the Venusian spectra, I read off the terrestrial values from the published graph and simply divided by the corresponding spectral solar constant values. The result is shown in Fig. 2. The full and dashed curves are the Venusian spectra (Refs. 4, 7), the dashed line as corrected for water vapor absorption by the authors. The dash-dot curve is the terrestrial cirrus spectrum, reduced as above, and plotted in arbitrary units so that the maximum around λ 2.3 μ coincides with the Venusian curve. Considering this very preliminary reduction, the similarities between the terrestrial cirrus cloud and the Venusian features are striking indeed. Note in particular that a water vapor correction around λ 1.86 μ would further improve the similarities.

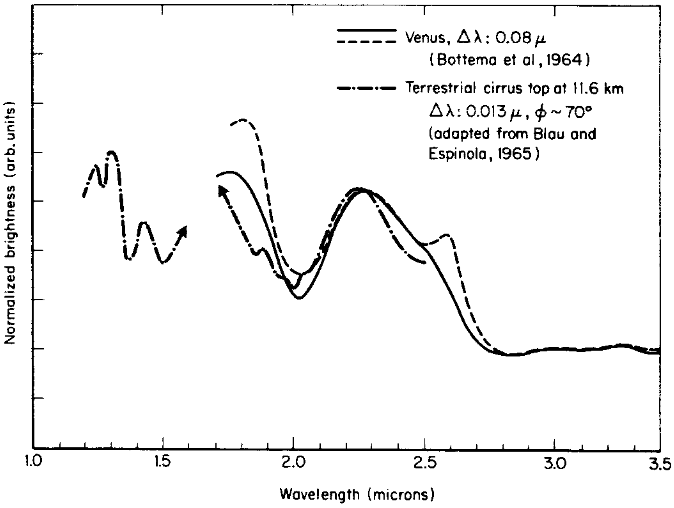

Fig. 2. Comparison of Venusian and terrestrial ice cloud spectra

Other terrestrial spectra in the report (Ref. 8), taken over dense water droplet clouds, are quite different. They show conclusively that in this case the same spectral region is dominated by the water vapor absorption bands around λ 1.86 μ. The difference between the spectra of water clouds and those of ice clouds could be explained in terms of (1) the effects on the albedo of single scattering, (2) the absorption bands in the water or ice phase *depending on the size and size distribution of the responsible particles*, and (3) the abundance of water *vapor* between particles.

The remarkable thing is that this kind of differentiation between the effects of vapor absorption and particle absorption, in the case of clouds, is likely to occur only in the infrared region in question, i.e., λ 1.5 to 3 μ. In other words, the Johns Hopkins group, either by design

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[1] Added in proof: See, however, R. Zander, 1966, *J. Geophys. Rev.*, Vol. 71, pp. 375–378, which appeared after this Conference.

[2] See, however, R. P. Espinola and H. H. Blau, 1965, *J. Geophys. Rev.*, Vol. 70, pp. 6263–6264, also published after this Conference.

or accident, chose to look at this significant part of the spectrum to obtain clear evidence of the existence of *ice* particles. Thus from a cursory comparison of the terrestrial and Venusian reflected spectra we can tentatively conclude that the latter represent infrared sunlight diffusely reflected by a dense, unbroken Venusian ice cloud layer. It would be hard to deduce any information on the presence or absence of a lower layer of water clouds from these data alone. I do have some suggestions on how to obtain such information.

First, allow me to make a few statements about the formation of absorption bands by scattering alone, and on cloud scattering in general. You will have to take my word for these until the appearance of detailed work, which I am in the process of preparing, on the nature of the scattering functions for various clouds, inside and outside regions of liquid water absorption.

For a given absorption band in the bulk material (water or ice):

1. The resultant absorption coefficient per particle depends very much on its relative size, the variation not being monotonic as a function of size.
2. The albedo of single scattering and hence the absorption coefficient per unit volume of polydisperse particles changes with the predominant size and the *size distribution* of the particles.
3. Multiple scattering may have two opposing effects on the intensity of an absorption band produced by scattering: In regions of strong absorption, the albedo of single scattering per unit volume is low, multiple scattering is suppressed, and the band will have essentially the central intensity given by the single-scattering process, but may show some broadening. In the region of very weak and narrow bands, the albedo of scattering is high, and multiple scattering will take place to some extent, resulting in some apparent deepening of the band at the center.
4. Since the degree of multiple scattering depends also on the available radiation, and since the scattering of infrared by cloud particles can be highly anisotropic (Ref. 9), there is also a *virtual anisotropy* in the albedo of single scattering and hence in the band shape and intensity. Therefore, for whole-disk spectra, these features will change with the planetary phase. If the disk can be resolved, there will also be a change with position on the disk.

All the remarks above apply to a hypothetical cloud with no humid air between particles; that is, the effects of water *vapor* absorption have not been mentioned. When we consider that in some regions the liquid and ice spectra are displaced with respect to the vapor spectrum, it becomes clear why it would be difficult to deduce liquid water and water vapor amounts from the spectra of sunlit clouds, without some rather sophisticated analysis. Chamberlain (Ref. 6) has recently discussed some of these difficulties in considering the problem of band formation on diffuse reflection.

As regards water droplet clouds, I have shown elsewhere (Ref. 9) that even in polydisperse clouds, certain features in the angular scattering pattern, at wavelengths where there is no absorption, are retained in the integrated single scattering phase function despite the many superpositions. Thus, for example, the cloudbow and the glory. Observation on natural clouds shows that these features are not quite suppressed by multiple scattering either, e.g., the commonly seen glories around the shadow point of aircraft overflying water clouds. I emphasize that these features are *not possible* with nonspherical particles; for example, randomly oriented prismatic ice crystals would not do. Hence, to determine whether the Venusian ice cloud overlies a lower deck of water clouds, I propose the following type of observation.

The object is to detect the glory that occurs in a ring about one degree wide and 2 to 5° radius around the subsolar point. To observe it one must have a large angular field of the medium available; in other words, it would be difficult to detect by terrestrial telescopy because the entire planet would be smaller than the feature. It is here that a flyby platform, similar to *Mariner II* and *IV*, with the planet subtending several tens of degrees rather than seconds of arc, would have a distinct advantage over terrestrial observations. It would be very easy to obtain the subsolar point and have a narrow-aperture photometer scan the area several degrees on either side. With a polarizer in two or three positions the experiment would be even more reliable since the glory has a definite polarization of opposite sign to that of the cloudbow occurring at about 38 deg from the subsolar point (Ref. 9).

As to the question of spectral region, if the visible spectrum is used, the chances of detecting the glory through an upper, optically dense, and unbroken ice cloud layer would be small. However, water-cloud glories exist also in the infrared in nonabsorbing regions. Choosing a narrow region around, say, λ 1.6 μ or λ 2.25 μ, where neither vapor nor liquid water has significant absorption bands, the chances of detecting the infrared glory are much improved, particularly in regions and at times of thinning of the Venusian ice cloud.

Such a deceptively simple experiment is well worth trying, because if any kind of glory-like phenomenon is detected, it would supply us with rather reliable evidence of the existence of water droplet clouds below the visible surface, and hence of considerable water substance in the atmosphere. If, on the other hand, the results of the experiment are negative and the existence of ice particles is confirmed, we must conclude that the Venusian ice cloud layer is optically dense in the infrared and we have to think of other methods of finding out what lies below it. We cannot think of alternate methods, however, short of actual probing of the clouds. By terrestrial analogy it is difficult to conceive a dense, unbroken ice cloud surrounding the planet without assuming a lot of water substance in the lower, denser, and warmer regions of the atmosphere.

Finally, let me refer to a recent paper by A. D. Kuzmin (Ref. 10)[3] which has just become available in English translation. In it the author arrives at the conclusion that the particulate matter is composed of aerosols of a polar liquid in the form of "functional derivatives of methane, ethane, and benzene." Considering the complex radiative processes in a sunlit atmosphere containing large particles, we can hardly justify his derivation of fundamental properties of the particulate substance, such as the relaxation time of the assumed organic molecules, on the basis of the observed planetary spectrum unless there are other convincing and concurring pieces of evidence. Granted that the *microwave* region could be thus interpreted, the particles must still act as strong scatterers in the visible and infrared to fit the observations.

In view of our present ignorance of the nature of the [illegible] of the Venusian atmosphere, and as I tried to argue elsewhere (Refs. 1, 2), the assumption of water substance (including water drops measuring a few millimeters in diameter) seems to be the most logical and natural one so far, capable of explaining most observables, including the microwave brightness. Extensive and detailed model-making at this stage cannot be very productive without more reliable data, I therefore merely sketched a tentative concept of the watery atmosphere, suggesting that an overall water content of 10 gm cm^{-2} is sufficient as a working hypothesis. I even went so far as to suggest that the existence of three distinct particulate layers would not contradict the observations: a lower, liquid water cloud with an optical thickness of the order of 100 in the visible and infrared; separated from this by a few kilometers of "clear" air, an intermediate ice cloud layer of optical thickness 10^{-1} to 1 in the same spectral region; and a superior layer several tens of kilometers above the ice cloud, in what may be the coldest region of the Venusian atmosphere, with an optical thickness of 10^{-3} or less in the visible, responsible for the well known elongation of the horns of Venus.

Note that the assumption of a certain number of raindrop-size water particles in suspension is an essential feature of our conceptual model (Refs. 1, 2). This assumption, by the way, could provide an alternate explanation for the apparent temperature differences between the sunlit and dark hemispheres, deduced from the microwave brightness, and between the "polar" and "equatorial" regions, deduced from the differential polarization at λ 10.6 cm, recently observed by Clark and Kuzmin (Ref. 11). One merely has to consider the temporal or spatial variations in the amount of these larger hydrometeors over the planetary surface and their ability to attenuate and polarize the microwaves emitted at the surface by absorption and scattering (Ref. 12). This is without even considering hailstone-sized particles, which might very well exist under these conditions, and which would further affect the emergent microwave radiation.

In conclusion, may I reiterate my belief that it is not possible to derive the nature of the *gaseous* component of the Venusian atmosphere from the observed spectrum, brightness, and polarization alone, without definite knowledge of the nature of the *particulate* component. Along these lines, and as early as July 1960, we had submitted formal and detailed proposals to the pertinent NASA agencies for a Venus flyby photopolarimetric experiment in narrow spectral bands covering the visible through the infrared up to λ 2.5 μ. A similar experiment incorporating also the glory scan outlined above should be within the capabilities of a new Venus flyby package and still worth the moderate effort involved, in view of the scientific payoff.

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[3] See also Dr. Kuzmin's "Some Remarks Concerning the Radio-astronomical Observations of Venus" in these *Proceedings.*

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