Reflectance and albedo differences between wet and dry surfaces

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It is commonly observed that natural multiple-scattering media such as sand and soils become noticeably darker when wet. The primary reason for this is that changing the medium surrounding the particles from air to water decreases their relative refractive index, hence increases the average degree of forwardness of scattering as determined by the asymmetry parameter (mean cosine of the scattering angle). As a consequence, incident photons have to be scattered more times before reemerging from the medium and are, therefore, exposed to a greater probability of being absorbed. A simple theory incorporating this idea yields results that are in reasonable agreement with the few measurements available in the literature, although there are differences. Our measurements of the reflectance of sand wetted with various liquids are in reasonably good agreement with the simple theory. We suggest that the difference between reflectances of wet and dry surfaces may have implications for remote sensing.

I. Introduction

Everyone is familiar with the fact that sand, clay, and similar natural surfaces, as well as many other powdered materials, become darker when wet. One of the most dramatic modifications of regional reflectance that has been observed and recorded (other than snow and cloud cover) was obvious darkening of an extensive area of Texas seen in photographs transmitted by Gemini 4 and reproduced in the *Bulletin of the American Meteorological Society* (Ref. 1, Fig. 5; see also Ref. 2). We have been unable to find a convincing discussion of the physical mechanism responsible for this darkening, even though it is so familiar.

In this paper we describe a mechanism for the darkening of surfaces on wetting and give a simple theoretical analysis of this mechanism. We also give some results of simple experiments. (Albedo as used herein is equivalent to irradiance or flux reflectance: the ratio of reflected irradiance to incident irradiance; in general, it depends on the direction of incidence. We reserve the term reflectance for what is often called bidirectional reflectance—a function of both directions of incidence and of reflection—and adopt a normalization in which a perfect Lambertian reflector has a reflectance of unity in all directions.)

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II. General Discussion

When sand or soil is wetted thoroughly, interstitial air (refractive index $m_0 = 1.0$) is replaced by water ($m_0 = 1.33$). For a given particle with refractive index m and diameter d, the optical effective size $[(m - m_0)/m_0]d$ (see, e.g., Ref. 3, p. 176) is thereby reduced. At first sight this would seem to provide an explanation for the observed darkening, but in soils, sand, etc. the particles are much larger than the wavelengths of visible light, and size, therefore, does not greatly affect the scattering efficiency, which for all practical purposes has its asymptotic value of ~ 2. Thus an explanation based on effective size cannot be entertained.

Basic physics dictates that discrete particles embedded in a continuous medium must be invisible (optically undetectable) if the refractive indices of particle and medium are exactly equal. Christiansen filters and immersion methods for refractive-index determination are straightforward applications of this principle, and they are not restricted to particles of any special size or shape.

Light scattering theory shows that the asymptotic value for the radiant power removed by a sphere of radius r from an incident beam of irradiance F_0 is $2\pi r^2 F_0$. This value is obtained approximately if r exceeds 10–20 wavelengths (see, e.g., Ref. 4, p. 297); the so-called extinction paradox refers to the presence of the factor 2, giving $2\pi r^2$ rather than just area πr^2. If there is no absorption, the power $2\pi r^2 F_0$ is redistributed as scattered radiation, and this asymptotic value is independent of refractive index. Thus there is an apparent conflict between these two fundamental results, since one implies that scattering by a large particle does not decrease as its refractive index approaches that of the surrounding medium, whereas the other dictates that there can be no scattering when the refractive indices are equal.

This apparent paradox is resolved if we consider the angular distribution of the scattered light: it is more and more concentrated around the forward direction as the refractive indices tend to equality and exactly forward when they are equal (i.e., a nonevent—the scattered wave is indistinguishable from the incident wave). This effect is shown in a brief table reproduced by van de Hulst (Ref. 3, p. 226) from Debye's thesis[5] and is confirmed by Mie computations (see, e.g., Fig. 12 in Ref. 6). Figure 1 of the present paper shows the asymmetry parameter g (i.e., mean cosine of the scattering angle) as a function of the ratio of particle refractive index m to that of the surrounding medium m_0. The increasing degree of forwardness as the refractive indices of particle and medium move closer together illustrates what will be the pivotal point in our discussion.

If we turn now to diffuse reflection by multiple-scattering from soil, sand, powders, etc., it is apparent that if such materials could be wetted with a liquid having a refractive index exactly equal to that of the solid particles (for the moment assumed uniform in optical properties and nonabsorbing), they would be invisible since no photons could be deflected from their original direction of travel. Real solid particles are, of course, nonuniform in composition, absorb to some extent, and usually possess higher real refractive indices than water and most liquids; when they are wetted the result is not total darkening, but the mechanism is the same: scattering becomes more forward, more scattering events are, therefore, needed to turn a photon around, and since each scattering involves a finite probability of absorption, fewer photons survive the greater number of scattering events so reflection is diminished.

As a simple example, consider a hypothetical medium that scatters all photons at 30° only, so that a minimum of four scattering events would be needed before a normally incident photon could escape. If there is one chance in twenty of absorption in each event, reflected photons will be less than $(0.95)^4$ or 81.5%, of the incident stream. Now change the scattering angle to 10°; at least ten scattering events are needed, and no more than $(0.95)^{10}$ or 60%, of the incident photons can emerge, which represents appreciable darkening even though the probability of absorption remained exactly the same for each individual scattering event.

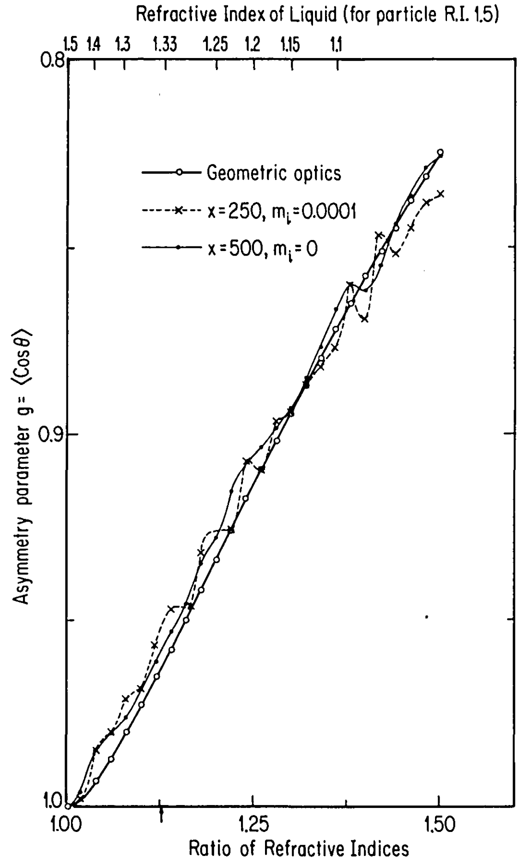

Fig. 1. Dependence of the mean cosine of the angle of scattering by a sphere (asymmetry parameter) on the refractive index (real part) relative to that of the surrounding medium. These calculations were made using both Mie theory and geometrical optics. The size parameter x is the sphere circumference divided by the wavelength, and m_i is the imaginary part of its refractive index.

III. Derivation of Approximate Formulas

Intuitively, it is obvious that a scattering event which deflects the average direction of propagation by, say, 10° must be less effective (for reflection by multiple scattering) than one which deflects it by 30°. If photons were scattered in only the forward (0°) and backward (180°) directions, the probability of forward scattering being f, then $1 - f$ would be the fraction of incident photons turned back in one scattering. In defining optical path length τ, as customarily used, no distinction is made between scattering into small angles and scattering into large angles. Although $\exp(-\tau)$ gives the fraction of photons not scattered after traversal of an optical path length τ, a more informative quantity (in this extreme case at least) would be $\exp[-(1 - f)\tau]$, which gives the fraction of incident photons which are either unscattered or scattered through 0°. In reality, scattering distributes photons over all directions, and the asymmetry parameter $g = \langle\cos\theta\rangle$, the cosine of the scattering angle averaged over many single-scattering events, indicates how forward-directed a scattering process is. This quantity can be computed for any scattering diagram, and for spherical particles can be obtained directly from the Mie coefficients. Generalizing from the extreme example of only forward and backward scattering, one might reasonably expect a scaled optical thickness $\tau' = \tau(1 - g)$ to be a better indicator of multiple-scattering properties than τ alone. Numerical tests confirm this expectation: for example, computations show that two scattering layers have almost the same reflection and transmission if $\tau(1 - g)$ has the same value for each even though the separate values of τ and g are different.

Up to this point we have neglected absorption. Sand, soil, and similar natural finely divided materials are, however, far from perfectly white even though essentially of infinite optical depth. When absorption is present, the fraction of photons surviving an encounter with a particle is $\bar{\omega}_0$ rather than unity, and τ is composed of a component $(1 - \bar{\omega}_0)\tau$ due to absorption and a scattering component $\tau\bar{\omega}_0$. The single-scattering albedo $\bar{\omega}_0$ for many, but not all, common particulate materials is close to unity; for such materials high orders of scattering occur and contribute substantially to reflection, since after n scatterings a fraction $\bar{\omega}_0{}^n$ remains unabsorbed [e.g., $(0.99)^{20}$ is greater than 0.8, and $(0.99)^{100}$ is 0.37].

The asymmetry parameter clearly has no direct relevance to absorption, so the group $(1 - \bar{\omega}_0)\tau$ should remain unchanged after scaling. Hence two layers with properties $(\tau', \bar{\omega}_0', g')$ and $(\tau, \bar{\omega}_0, g)$ are predicted to be similar in their overall multiple-scattering properties (e.g., reflection, absorption, transmission) if

$$(1 - \bar{\omega}_0')\tau' = (1 - \bar{\omega}_0)\tau,$$
$$(1 - g')\bar{\omega}'_0\tau - (1 - g)\bar{\omega}_0\tau. \qquad (1)$$

These scaling or similarity relationships, which were first used for multiple light scattering by van de Hulst and Grossman,[7] have been amply validated by numerical tests (see Ref. 8, p. 398 and elsewhere). It is noteworthy that, whereas with conservative scattering (no absorption) all infinitely deep layers are similar whatever the degree of asymmety ($\bar{\omega}_0' = 1$ and $\tau' \to \infty$ as $\tau \to \infty$ for $g = 1$), this is not true in the nonconservative case: $\bar{\omega}_0'$ is a function of asymmetry for $\bar{\omega}_0 \neq 1$. By division, a scaling formula is obtained from Eq. (1) which does not contain optical thickness and so can be applied for any τ; this is further simplified if g' is stipulated to be zero meaning that an optically deep layer with actual properties $(\bar{\omega}_0, g)$ will be approximated by an isotropically scattering deep layer with a single-scattering albedo $\bar{\omega}_0'$ given by

$$\bar{\omega}_0' = \bar{\omega}_0 \frac{1 - g}{1 - g\bar{\omega}_0}\,. \qquad (2)$$

Note that this scaled (or effective) single-scattering albedo depends strongly on the asymmetry parameter g and goes to zero as g goes to unity. If $\bar{\omega}_0 = 0.9$ and $g = 0.9$, for example, the scaled value for a layer with $g' = 0$ is $\bar{\omega}_0' = 0.47$, substantially less than 0.9. The dependence of $\bar{\omega}_0'$ on g is shown in Fig. 2. It is notable that for a typical particle refractive index (~1.5), the change from a medium with $m_0 = 1.0$ (air) to $m_0 = 1.33$ (water) increases the asymmetry parameter from around 0.8 to ~0.97 (see Fig. 1), which coincides with the region in Fig. 2 where $\bar{\omega}_0'$ changes rapidly with g. Wetting, therefore, reduces the scaled single-scattering albedo although the actual single-scattering albedo is the same or almost the same.

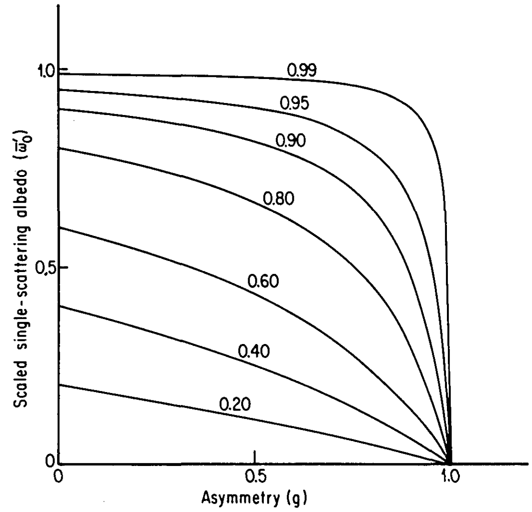

Fig. 2. Scaled single-scattering albedo vs asymmetry parameter. Curves are labeled with the actual (unscaled) single-scattering albedo.

A one-to-one relationship exists between reflectance and single-scattering albedo for an infinitely deep isotropic layer, and fairly simple formulas have been derived for that case by Chandrasekhar.[9] His treatment shows that a radiant flux (irradiance) F_0 incident at zenith angle $\cos^{-1}\mu_0$ gives rise to a (multiply scattered) reflected intensity (radiance)

$$I(\mu) = \frac{1}{4\pi}\frac{\bar{\omega}_0\mu_0}{\mu + \mu_0} H(\mu)H(\mu_0)F_0, \qquad (3)$$

where μ is the cosine of the direction of the reflected intensity. The H functions are smooth and monotonic, being unity at argument zero for all $\bar{\omega}_0$ and reaching a maximum between 1 and 3 at argument unity depending on the value of $\bar{\omega}_0$; values of $H(\mu)$ are tabulated in Ref. 9 (p. 125), and they can be computed readily by iteration on any small computer. The albedo (irradiance or flux reflectance) is obtained by integrating $I(\mu)$ over all μ and can be shown to be (see, e.g., Ref. 10)

$$R = 1 - \sqrt{1 - \bar{\omega}_0}H(\mu_0). \qquad (4)$$

Equations (3) and (4) give reflectance and albedo as functions of single-scattering albedo for an infinitely deep layer of isotropic scatterers. Real particles do not scatter isotropically, so Eqs. (3) and (4) are not directly applicable, but by scaling we can find an isotropic layer which is similar to (i.e., closely approximates) the anisotropically scattering layer of interest; hence we can apply Eqs. (3) and (4) (as approximations) to anisotropic scatterers but must use $\bar{\omega}_0'$ in place of $\bar{\omega}_0$ in these equations.

Although the single-scattering albedo $\bar{\omega}_0$ of particles in natural scattering layers is not known, the scaled single-scattering albedo $\bar{\omega}_0'$ is by Eq. (4) directly inferable from the reflectance. We have plotted in Fig. 3 the relationship between scaled single-scattering albedo and both zenith reflectance [Eq. (3)] and albedo [Eq. (4)] for incident illumination at 41.4° from the zenith ($\mu_0 = 0.75$).

Wetting a finely divided material increases the asymmetry parameter g and hence, according to Eq. (2), decreases the scaled single-scattering albedo $\bar{\omega}_0'$. For particles that are large compared with the wavelength, the asymmetry parameter is almost independent of size, being determined primarily by the ratio of particle refractive index to that of the surrounding medium (Fig. 1). Given the reflectance or the albedo of the dry surface, the value of $\bar{\omega}_0'$ is obtained from Fig. 3. The value of $\bar{\omega}_0'$ when the surface is wet can then be obtained from the expression

$$\bar{\omega}_{0\text{wet}}' = \frac{r\bar{\omega}_{0\text{dry}}'}{r\bar{\omega}_{0\text{dry}}' + 1 - \bar{\omega}_{0\text{dry}}'}, \quad r = \frac{1 - g_{\text{wet}}}{1 - g_{\text{dry}}}, \tag{5}$$

which results from applying Eq. (2) for both wet and dry conditions. For weakly absorbing particles larger than the wavelength, the actual single-scattering albedo $\bar{\omega}_0$ is not substantially changed by wetting, whereas the scaled value $\bar{\omega}_0'$ is.

As a numerical example, consider a surface which when dry has a reflectance of 0.3 for the illumination envisaged in Fig. 3; this figure shows the corresponding value of $\bar{\omega}_0'$ to be 0.825. If a particle with real refractive index 1.5 (typical of sand and many common minerals at visible wavelengths) is surrounded by water ($m_0 = 1.33$) instead of air, the relative refractive index is reduced to 1.13, and from Fig. 1, the asymmetry parameter increases from ~0.83 to 0.96, giving for the ratio r in Eq. (5) the value 0.23. Thus wetting reduces $\bar{\omega}_0'$ from 0.825 to 0.52. According to Fig. 3, the corresponding reflectance is 0.12, less than half of the original reflectance. The procedure for determining wet from dry reflectances is outlined schematically in Fig. 4.

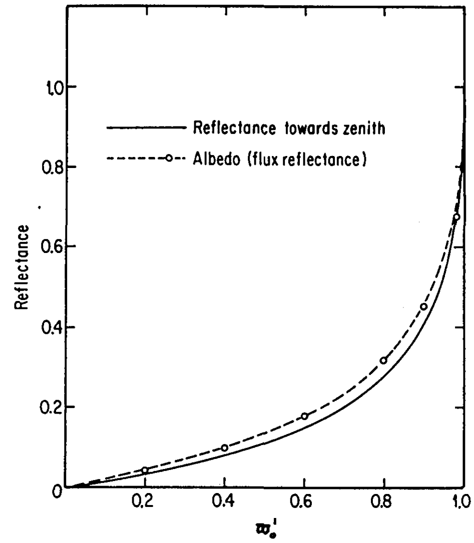

Fig. 3. Dependence of albedo and zenith reflectance (for incident light at 41.4° from zenith) on scaled single-scattering albedo $\bar{\omega}_0'$.

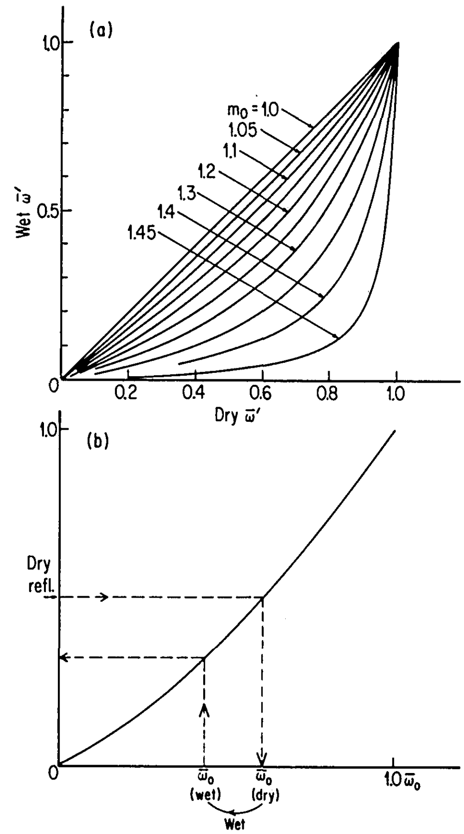

Fig. 4. (a) Scaled single-scattering albedos for an infinitely deep scattering layer wet by a liquid with refractive index m_0. The particles are much larger than the wavelength and have a refractive index of 1.5. (b) Inference of the reflectance produced by wetting.

IV. Predictions of the Effect of Wetting on Albedo and Reflectance

A. Wetting of Sand and Soil

Natural surfaces are wetted on a large scale only by water; for a typical particle refractive index—few naturally occurring common materials differ markedly from 1.5—wet albedo can be predicted from dry albedo in a manner similar to that described in the previous section. Few data on albedos (or reflectances) of natural surfaces in both wet and dry states could be found in the literature; what we have been able to find is shown in Fig. 5.

The greatest relative change in albedo on wetting occurs for dry albedos around 0.3–0.6, which decrease by ~0.1. (An albedo of zero implies total absorption, whereas an albedo of unity implies no absorption whatsoever, so neither of these extreme values is changed by wetting.)

B. Experiments Using Liquids of Different Refractive Indices

Figure 6 shows a photograph[11] of sand that was wet with water and benzene. It is readily apparent that the liquid of higher refractive index (benzene) produced a darker surface than the liquid of lower refractive index (water), as argued in the preceding section.

Quantitative tests of this were made by wetting various surfaces (sand, soil, concrete) with liquids of different refractive index—glycerol, benzene, carbon disulfide, sugar solutions—in sunlit conditions and observing the change in the reading of a photometer viewing the test surfaces. (In most experiments, a

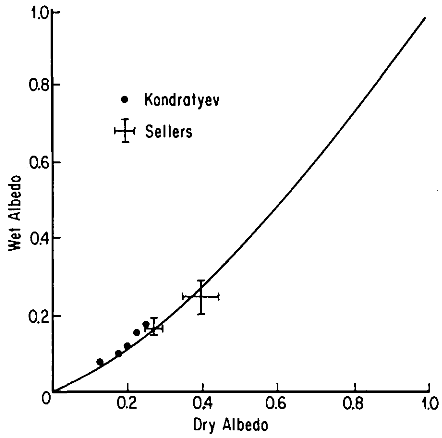

Fig. 5. Wet vs dry albedos obtained by the method indicated in Fig. 4. The wetting liquid is water ($m_0 = 1.33$). The crosses are experimental data given by Sellers[13] for natural surfaces; the circles are similar experimental data reported by Kondratyev.[15]

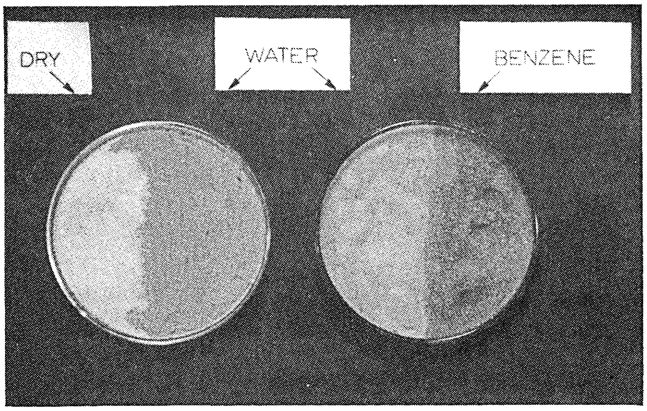

Fig. 6. Sand wet by water and benzene (from Ref. 11).

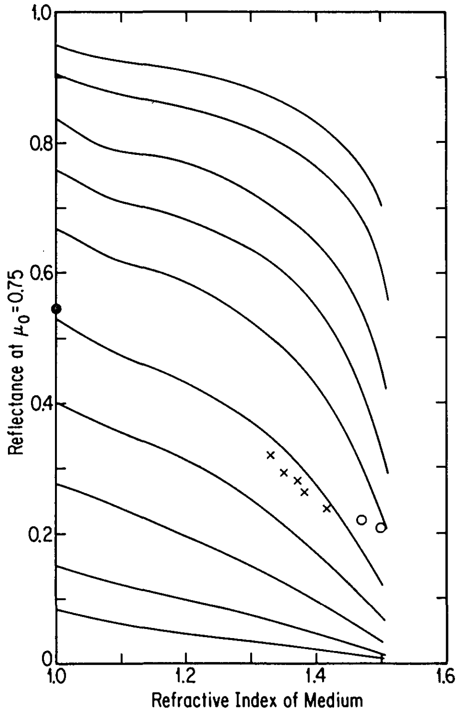

Fig. 7. Computed curves of zenith reflectance for a range of values of (unscaled) single-scattering albedo. The dark circle shows the measured value for Ottawa sand before wetting. The crosses are experimental results for wetting by sugar solutions with refractive index ranging from 1.33 to 1.48. The open circles are for wetting by benzene and glycerol.

small fiber-optic pickup was used.) Before and after introduction of the test surface, a reference surface (white paper or an NBS-calibrated standard diffuser) was brought into the sensor field of view, enabling both relative and absolute reflectances to be inferred. No attempt was made to infer albedos since this requires integration over all directions. The theoretical expressions given earlier had the single-scattering albedo $\bar{\omega}_0$ as a variable, which is not controllable but rather an externally prescribed unknown. (Absorption in these surfaces is a result of traces of impurities rather than an intrinsic property of either the bulk material or the surrounding medium.) Ideally, $\bar{\omega}_0$ would be varied and dry and wet reflectances measured for different wetting liquids, but this is not possible in practice. One can only infer $\bar{\omega}_0'$ from one measurement (dry reflectance) and then compare the wet reflectance to the theoretical prediction.

All our experiments gave similar results; rather than present all of them, we restrict ourselves to those obtained with Ottawa sand wetted by aqueous sugar solutions, the refractive index of which can be varied by changing the concentration,[12] and a few results for benzene and glycerol. The results are plotted in Fig. 7; the reflectance and liquid refractive index are the dependent and independent variables, respectively, directly pertaining to the experiment. The sets of curves in this figure are for different values of the absorption coefficient of the particles, which is the most important parameter in calculations; $\bar{\omega}_0$ was calculated using Mie theory, strictly applicable only to spheres of uniform composition, which assuredly the experimental particles were not. The data points lie close to one of the theoretical curves but do not coincide exactly with any of them. Considering the nonuniformity of real materials, the degree of agreement seems satisfactory for sugar solutions, somewhat less than satisfactory for benzene and glycerol.

C. Angular Distribution of Reflectance

From the theory developed previously the angular distribution of reflectance and the dependence of albedo on the direction of illumination are given by H functions [Eqs. (3) and (4)]. When theoretical predictions are compared to some data from the literature (e.g., Ref. 13), the disagreement is serious: the computed variation of albedo with direction of incident illumination is much less than that given in this reference. However, measurements obtained by hemispherical omnidirectional sensors are subject to considerable errors; albedos obtained by Kuhn and Suomi[14] by integration of directional data showed only a slight variation with solar angle compared with a very

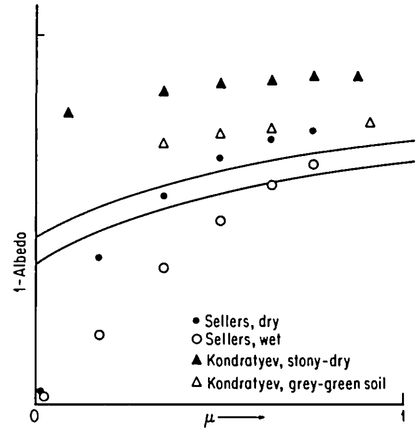

Fig. 8. Calculated dependence of albedo (for representative single-scattering albedos) on the direction of incident illumination [Eq. (4)] compared with data from Sellers[13] and from Kondratyev.[15]

strong variation obtained when a hemispherical instrument was used. Albedos tabulated by Kondratyev,[15] in marked contrast with those presented by Sellers,[13] varied only ~10% over all solar angles. The curves in Fig. 8 show computed directional dependence for several values of $\bar{\omega}_0'$ together with data from Refs. 13 (p. 30) and 15 (Table 4.10). Equation (4) gives a dependence similar to that of the Kondratyev data; the data of Sellers, however, are very different, so no conclusive judgment can be made concerning the adequacy of the theory.

Although for convenience we have cited Sellers as the source of the albedo data shown in Fig. 8, they are not his measurements. He obtained them from another secondary source[16] in which the measurements made originally by Büttner and Sutter[17] are presented. These authors did not measure albedos for solar elevations of less than ~20°; albedos for elevations less than this were obtained by extrapolation. So the sharp increase in albedo with decreasing elevation may be what the authors expected it to be rather than what it really was. If one looks at sand (both wet and dry) in various directions, it is difficult to accept that its albedo is almost 100% at near-glancing incidence, unless, of course, the sand is completely covered by water.

V. Other Darkening Mechanisms

Although we have argued that the mechanism for darkening of sand on wetting is increased forward scattering by the sand grains, there are other possible mechanisms which must be addressed. For example, in going from one homogeneous (nonabsorbing) medium to a different one, radiance is not conserved (even if the transmittance is taken to be unity) but rather the product of radiance and refractive index squared. This result has been derived by Milne (Ref. 18, p. 74), for example, although it was known to Planck (Ref. 19, p. 35) and even earlier to Helmholtz (Ref. 20, p. 233).

Consider, for example, light transmitted from water to air. The transmitted radiance is (ignoring transmission losses) less than that incident by the factor $1/m_0^2$, where m_0 is the refractive index of water. The physical reason for this is that refraction causes an incident bundle of rays to occupy a larger solid angle on transmission; although the amount of radiant energy has not changed, its disposition has. Thus, in proper circumstances, the radiance of an object under water may be less than above water by the factor $1/m_0^2$.

This can be demonstrated easily enough with a few pans of water and a white plastic spoon. What is observed depends on the nature of the pan (white or dark) and even which side of the spoon one faces. If its bowl is partially submerged in water in a dark pan, the submerged part is noticeably darker than the part above water provided that one faces the convex side of the bowl one faces. But now turn the spoon over so that one faces the concave side one faces. In this case the submerged part will not be so noticeably darker than the part above water. Now repeat this experiment using a white pan filled with water. The darkening is hardly noticeable at all, regardless of the orientation of the spoon.

This geometrical mechanism for darkening of objects under water, which does not entail a change in their reflecting properties, depends on the extent to which multiple reflections are important. A perfectly white object, infinite in lateral extent, will be no less bright under water than above water because under water it is illuminated not only directly but indirectly as the result of many multiple reflections between it and the water–air interface. Only in the limiting case of an object not illuminated by any multiply reflected light (either because it or its surroundings are black) will its reflectance be reduced by $1/m_0^2$ when it is under water. All other objects will suffer radiance reductions lying between these two extremes. A white spoon, for example, suffers different amounts of brightness reduction when submerged depending on the extent to which it is illuminated indirectly as well as directly, which in turn depends on its orientation as well as the nature of its surroundings under water.

What we have called the geometrical mechanism for the reduction of the albedo of ground on wetting was put forward by Angström.[20] He recognized that the magnitude of the reduction depends on the albedo of the ground when dry, and he even gave an explicit expression for the dependence of wet albedo on dry albedo and the refractive index of the wetting liquid. But he also stated emphatically that the "diffuse reflection power of the surface ... is assumed to be unaltered through the presence of the liquid." We have argued the contrary: wetting changes the diffuse reflection power by making the scattering more forward. To determine which mechanism is dominant, recourse must be had to measurements.

If measurements were made using only water as the wetting liquid, it would be very easy to conclude that the geometrical mechanism proposed by Angström is indeed responsible for the observed darkening. It is only when liquids with different refractive indices are used that the issue can be settled. If, for example, the geometrical darkening mechanism were dominant, the reduction in reflection in going from a wetting liquid with refractive index 1.35 to one with refractive index 1.4 could be at most ~7%, whereas the data of Fig. 7 show a reduction of ~40%. We, therefore, conclude that at least for the case we have investigated geometric darkening is of considerably less magnitude than that wrought by increasing the forwardness of scattering by grains.

There is yet another mechanism for darkening, which at first glance may seem different from the one we have discussed. Suppose that instead of a medium consisting of more or less distinguishable grains, we have a homogeneous medium with a rough surface. Frosted glass is a simple example. When such glass is wet by water it becomes noticeably darker. We argue that this is merely a variation on a theme: wetting the glass makes the scattering more forward (i.e., more light is transmitted into the glass rather than being diffusely reflected by it).

VI. Concluding Remarks

Apart from offering a straightforward physical explanation of a very common observation, the theory developed here would appear to be relevant to remote sensing: it suggests inclusion of wet, as well as dry, spectral reflectance for characterizing natural surfaces (other than dense vegetation). Since the refractive index of the wetting liquid is accurately known, one can characterize the complex refractive index (or its effective value for the real nonuniform world) much better by two measurements than by a single measurement. We also note that the extent to which a surface darkens on wetting decreases with increasing (real) refractive index of the surface material, which may have implications for remote sensing.

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