Polarization and scattering characteristics in the atmospheres of Earth, Venus, and Jupiter

David L. Coffeen
Goddard Institute for Space Studies, 2880 Broadway, New York, New York 10025
State University of New York, Stony Brook, New York 11794
(Received 22 January 1979)

Our understanding of atmospheric scattering phenomena has increased through the combined developments of new electro-optical instrumentation, theoretical solutions for complex model atmospheres, and large computers enabling computation of such solutions. Earth satellites permit external, planetwide observations of our atmosphere, while spacecraft permit detailed measurements of the scattering by other planetary atmospheres. Some recent results are: elucidation of the effects of ozone absorption and high-altitude aerosol scattering on twilight colors and polarization; identification of a cloudbow on Venus and consequent deduction of the cloud particle shape, size distribution, and refractive index; and, the interpretation of Rayleigh scattering on Jupiter in terms of cloud-topography.

“This most excellent canopy, the air, look you, this brave o’erhanging firmament, this majestical roof frettet with golden fire, why, it appears no other thing to me but a foul and pestilent congregation of vapours.”
—William Shakespeare, Hamlet, Act 2, Scene 2.

Hamlet’s statement provides an overview of my paper, for I shall speak of the air, the firmament, the golden fire, and the vapors. For three planets—Earth, Venus, and Jupiter—scattering by gas, haze, and clouds will be discussed. As it is difficult to present a comprehensive review of atmospheric scattering, I shall touch on various bits of exciting progress, and open questions, as seen from my own biased viewpoint. I will differentiate between internal (observer within the atmosphere) and external (observer outside) conditions, and between “daylight” (i.e., direct) illumination and “twilight” illumination (i.e., in or near shadows). The key to understanding many of the optical phenomena is to separate the variables and unscramble the various influences. I will discuss all four Stokes’ parameters (equivalent to the intensity, the degree of linear polarization, the direction of vibration, and the degree of circular polarization), employing whichever seems most useful as a diagnostic for a particular scattering situation. The degree of linear polarization will be emphasized, as it is particularly important for deducing shapes, sizes, and refractive indices of scattering particles. I believe this discussion of polarization falls well within the charter of Meteorological Optics; the eye has considerable ability to detect linear polarization and its direction, and apparently can sense circular polarization and its handedness. Finally, I will address future directions of research.

EARTH

The title of this paper is adapted from that of an excellent review written 30 years ago by van de Hulst. Fundamental changes have taken place since then in our perception, and perspective, of the Earth and its atmosphere. We have surveyed the process of twilight from outside the atmosphere in Earth orbit, watched earthrise on the moon, and observed the Earth eclipsing the sun. We now sense the Earth as a planet. At the same time we have developed powerful tools for understanding the more traditional aspects of scattering, with advanced instrumentation permitting speed, accuracy, wavelength coverage, and automatic processing of data; theoretical solutions permitting accurate formulation of the scattered radiation field for inhomogeneous, turbid, model atmospheres of arbitrary optical depth; and, large scale computers enabling the calculation of the scattered intensity and polarization for almost any such model atmosphere. For salient reviews of traditional areas of Earth atmospheric-scattering phenomena, I recommend nine books and monographs.

Daytime sky

The intensity due to single scattering by molecules (or by density fluctuations in the gas) is proportional to factors involving the wavelength , the gas refractive index , the molecular depolarization factor (a small number, equal to the ratio of intensities parallel and perpendicular to the plane of scattering, for the light scattered by °), with the incident light unpolarized; for air, °, and the scattering angle (the angle by which the light beam is deviated):

The scattered light is blue; the wavelength dependence is approximately , deviating slightly owing to dispersion of the refractive index. The scattered intensity is twice as bright in the forward and backward directions as it is at °.

If a parcel of gas is illuminated by an unpolarized light beam (i.e., a beam having equal intensities for all possible orientations of the electric vector maximum about the direction of propagation), the light scattered into some direction will be linearly polarized, with a preponderance of the electric vector maxima oriented perpendicular to the plane of scattering (the plane containing the incident and emergent light beams). The degree of linear polarization is independent of wavelength and is given by

Thus the degree of polarization is zero in the forward and backward directions, reaching a maximum of 1.00 (or 100%) at a scattering angle °, for perfect Rayleigh (molecular) scattering. The effective molecular anisotropy of air (° ~ 0.03) reduces the maximum polarization to 94%. The di-
FIG. 1. "Neutral lines," the boundaries between regions of positive and regions of negative polarization, in the clear daytime sky. The entire hemisphere of the sky is shown, with altitude circles every 10°. Neutral lines are given for each of seven different zenith angles of the sun, ranging from 30° to 87°. On the left are observations made by Dorno on 17 May 1917 at Davos, Switzerland; on the right are computations for multiple Rayleigh scattering using Chandrasekhar's solution. The neutral lines intersect the solar vertical plane on the well-known neutral points of zero polarization, the Brewster, Babinet, and Arago points. These points and the shapes of neutral lines result from multiple scattering within the molecular atmosphere. The excellent agreement between observations and theory is evidence for the correctness and applicability of Chandrasekhar's solution (after Chandrasekhar and Elbert14).

rection of vibration of the maximum electric vector, for single scattering by a gas, is always perpendicular to the scattering plane; this condition is termed positive linear polarization (negative refers to the electric vector maximum in the plane of scattering, which occurs in many cases of scattering by large particles). The degree of circular polarization for scattering by molecules is invariably zero.

These simple angular functions (phase functions) for intensity and degree of polarization are disturbed by several effects in the real atmosphere, especially multiple scattering, ground reflection, and the presence of aerosols. The first two effects (assuming Lambertian ground reflection) were included in Chandrasekhar's solution.13 This predicts the principal aspects we see in a clear sky: darkest ~ 90° from the sun, bright horizon (due to enhanced multiple scattering), and the blue color becoming pale at the horizon.

Multiple scattering creates net negative polarization in specific areas of the sky where the polarization by single scattering is weak. Continuity requires that there be places of zero polarization: the historic Babinet, Brewster, and Arago neutral points in the solar vertical plane. These neutral points lie on neutral "lines" that separate regions of positive from regions of negative polarization over the hemisphere of the clear daytime sky. One of the most elegant results of Chandrasekhar's theory is the comparison of the mapping of these neutral lines by Dorno and the calculations by Chandrasekhar and Elbert,14 shown in Fig. 1. The theory shows that as the ground reflectivity is increased, the degree of polarization generally decreases, but the neutral lines are relatively unchanged. As the optical depth of the atmosphere is increased, the regions of negative polarization enlarge, with the neutral points on the solar-vertical plane moving away from the solar and antisolar directions. With the recent study by Kattawar et al.,15 we can understand the behavior of the neutral points for a molecular atmosphere of arbitrary optical depth. Figure 2 shows the situation for a low sun (zenith angle 79°,15). In the limit of small optical depth the only zero polarization is in line with the sun. The neutral points form and

FIG. 2. Computed positions (μ = cosine of zenith angle) of the neutral points in the solar vertical plane in a clear Rayleigh atmosphere as a function of the vertical optical depth (τ). The sun is at 79°, 15 zenith angle; results are shown for two ground albedos (A). Note the divergence and eventual disappearance of the neutral points as the optical depth increases (after Kattawar et al.15).
FIG. 3. Typical scattering diagrams (phase functions) for six size distributions of dielectric spheres. Unpolarized light is incident from the left. The scattered intensity is plotted as a function of direction. The refractive index $m$, the wavelength $\lambda$, and the effective variance $V_{\text{eff}}$ of the size distribution are held constant while the effective radius $r_{\text{eff}}$ (nm) is varied.\textsuperscript{12}

As the circumference-to-wavelength ratio increases, the scattering becomes more concentrated about the forward direction. Thus the angular width of an aureole about the sun is an indication of the mean size of the atmospheric aerosols.

diverge as the optical depth increases. The Brewster point, upon reaching the horizon below the sun, is reinterpreted as the Arago point which rises above the antisolar horizon. At $\tau = 0.1$, corresponding to the vertical optical depth of the earth's clear atmosphere at $\lambda \approx 550$ nm, the Babinet point is $18^\circ.6$ above the sun; the Brewster point would be $18^\circ.6$ below the sun (thus $7^\circ.8$ below the solar horizon) and so is identified as an Arago point $7^\circ.8$ above the antisolar horizon. The maximum displacements occur at $\tau = 1.2$. Four neutral points occur between 1.2 and 1.8, in the absence of ground reflection. Finally, for $\tau > 2.5$ the neutral points are gone. The character of the sky has changed. There is nearly complete diffusion by multiple scattering, the downward emergent radiation having lost its "memory" of the incident direction of sunlight. For $\tau > 2.5$ the intensity distribution is circularly symmetric about the zenith, decreasing from zenith to horizon. The polarization at the zenith is zero; all around the horizon it is approximately 10%.\textsuperscript{15} A complete scattering theory and a large computer have shown us the full evolution of the neutral points.

Thus, scattering of light in the clear daytime sky seems well understood. Some "ground" surfaces are hardly Lambertian, e.g., the ocean surface, which efficiently directs and polarizes by specular reflection; and, surface topography can affect local scattering situations, e.g., in the shadow of a mountain (see "Shadows" section below). Otherwise the model is rather complete, and in agreement with the observations.

Suspended particles are the real challenge to model and to understand: dust, haze, and clouds, having complex geometries that change over time. The bright aureole around the sun is the most direct evidence of aerosols: its brightness related to the quantity of aerosols and its angular profile particularly related to the sizes of the particles. Thus the brightness gradient of the aureole immediately gives an estimate of particle size. The polarization will depend on particle shape, size(s), and refractive index, but the maximum polarization of the clear sky ($\sim 90^\circ$ from the sun) will generally be reduced by an aerosol presence. An example of this is given in Fig. 4, showing Coulson's\textsuperscript{16} measurements of the drop in polarization as Los Angeles smog builds up during the morning hours.

A striking indication of the stratification of aerosols in the atmosphere is given by measurements of the polarization of skylight, near the zenith, from a rising balloon platform. Figure 5 shows results by Unz.\textsuperscript{17} During ascent the polar-

FIG. 4. Measurements of the maximum degree of polarization (occurring $\sim 90^\circ$ from the sun, in the solar vertical plane) as a function of increasing solar elevation in clear (Davis and Los Angeles, California) and polluted (Los Angeles) atmospheres. Note the reduced value of the maximum in the polluted cases, and the rapid decrease during the day, attributed to build-up of smog and motion of the $90^\circ$-phase-angle point toward the horizon (after Coulson\textsuperscript{16}).
ization can increase or decrease depending on the ratio of aerosol optical depth to gas optical depth above the balloon at each instant. The measurements are inverted to yield the aerosol concentration as a function of height.

Aerosols are sometimes quite visible to the eye, as in the case of Sahara dust carried westward across the Atlantic to the Caribbean. Darwin, writing of his voyage on the Beagle, observed:

"Generally the atmosphere is hazy; and this is caused by the falling of impalpably fine dust, which was found to have slightly injured the astronomical instruments... From the direction of the wind whenever it has fallen, and from its having always fallen during those months when the harrassment is known to raise clouds of dust high into the atmosphere, we may feel sure that it all comes from Africa... The dust falls in such quantities as to dirty everything on board, and to hurt people's eyes; vessels even have run on shore owing to the obscurity of the atmosphere. It has often fallen on ships when several hundred, and even more than a thousand miles from the coast of Africa, and at points sixteen hundred miles distant in a north and south direction."

Flying at 15,000 feet or higher, west of the African coast, the ocean surface is frequently invisible, with only a uniform red haze showing. Is this color due solely to absorption, or does scattering play a role?

Nonabsorbing scatterers can effectively introduce color to themselves or to a light source. Figure 6 shows the total extinction efficiency for spheres of refractive index 1.33. The maxima and minima result from interference between the diffracted and transmitted beams. For nonabsorbing particles much smaller than the wavelength, the total scattering efficiency (into all directions) varies as $\lambda^{-4}$; the ratio $R$ of scattering at 400 nm to scattering at 700 nm will equal 9.4. This is the blue of the sky; distant dark mountains appear blue due to this "airlight." However, distant bright clouds appear yellow and the setting sun red, for the efficient scattering at short wavelengths has depleted this radiation from the bright source, while passing the longer wavelengths. Returning to Fig. 6, with a relatively narrow size distribution of larger particles (centered on 0.70-μm radius), the colors actually reverse ($R = 0.41$). The hazy sky would appear red (ignoring Rayleigh scattering by gas), and the bright source seen through the haze would appear blue (e.g., blue moon or sun). For much larger dielectric particles the scattering efficiency has little dependence on wavelength, so the scattering is neutral (white).

This brings us to water and ice clouds, usually white owing to particle sizes large compared with the wavelength of observation, and to lack of specific absorption features at visible wavelengths. A heavy overcast imposes many scatterings on transmitted photons; again the incident direction is forgotten, the sky brightness is symmetrical about the zenith, which is the brightest point (least line-of-sight optical depth of the cloud). The intensity drops toward the relatively dark horizon. This assumes a reasonably low ground albedo; for a very bright surface the observer can find himself immersed in a nearly isotropic illumination field—the "white-out" condition. Clouds will be discussed here in detail from the aspect of external observations of the "reflected" radiation (see "External" section below).

**Shadows in the sky**

By shading various parts of the scene we can facilitate the separation of variables. Twilight, the earth shadow, is most often studied. Direct illumination of the ground ceases at sunset and the shadow climbs, probing the atmosphere vertically. The problem is so complex, involving atmospheric conditions over great distances, strong refraction effects, and differing amounts of multiple scattering and absorption, that no satisfactory model has been created. On the other hand, this very complexity makes twilight analysis potentially the most productive. We are just beginning to understand twilight colors. The Chappuis band of ozone absorption, cen-
FIG. 7. Calculations of the brightness of skylight for the sun 60° below the horizon, as a function of wavelength and zenith angle of observation (in the solar vertical plane on the sunward side). The model includes spherical geometry, atmospheric refraction, scattering by gas and by standard aerosols, and ozone absorption, but is restricted to single scattering. The predominant colors of twilight are reproduced by the model. The minimum near 0.6 μm is due to ozone absorption, which is thus responsible for the purple and blue colors at twilight (after Adams et al.19).

FIG. 8. Observations of the polarization of the clear sky, near the zenith, as the sun rises. The data were taken in west Texas, at wavelengths of 355 nm (U), 529 nm (G), and 943 nm (I). The 94% polarization expected for single scattering by pure air is reduced by multiple scattering, by ground reflection (after sunrise), and by aerosol scattering (especially well before sunrise when the illuminated region may have a high aerosol-to-gas scattering ratio) (after Gehrels20).

FIG. 9. Observations of zenith sky polarization at sunrise taken from Mauna Loa Observatory, Hawaii, 19 February 1977. The structure at −6° to −3° sun elevation, in the infrared, is typical, although the position and depth of the minimum vary considerably from day to day, related to the atmospheric turbidity. The minimum at −4° indicates an aerosol layer with maximum density at −16 km (after Coulson21).

spherical geometry, atmospheric refraction, and aerosol scattering; the effect of ozone is impressive, although the model is not yet completely realistic. Sunset colors vary greatly. What causes the occasional greens? Does ozone alone explain the purple light? If so, why is the intensity of the purple light so variable, and why was it so intense following the 1963 Gunung Agung eruption (see Plate 111)?

The linear polarization of light from the zenith, during twilight, varies with solar elevation and wavelength. Figure 8 shows measurements by Gehrels20 made at McDonald Observatory in the hill country of west Texas. The polarization increases to a maximum just before sunrise, then decreases. Why is the polarization low at large solar depressions? Apparently, single scattering by molecules at high altitude is not the principal contribution, as this would show pure Rayleigh scattering (large maximum polarization at the zenith, ~90° from the sun). High aerosol layers could explain it (compare with Fig. 5). The polarization is generally lower in the ultraviolet, due probably to greater optical depth and, therefore, more multiple scattering at shorter wavelengths. The polarization in the infrared drops rapidly as the sun rises. This may be one of our unscramblings; the bright ground reflection (reddish soil and vegetation) significantly reduces the polarization in the red. Coulson21 has discovered a remarkable structure in the twilight zenith polarization curve in measurements from Mauna Loa, Hawaii. As shown in Fig. 9, a minimum occurs between sun elevations of −4° and −2°, at infrared wavelengths, the exact structure depending on the turbidity. Using this method Coulson proposes a useful
monitoring of upper atmosphere aerosols. For the full understanding of twilight we await better models.

Clouds and mountains cast shadows that eliminate direct single scattering and permit analysis of the multiply-scattered radiation. No one seems to have taken advantage of this opportunity, although Fraser (private communication) attributes the green color of severe thunderstorms to cloud shadowing at low sun elevations. Finally, if we wait for a total solar eclipse, we have a major shadow. During totality the zenith brightness drops sharply (although it still can include some single scattering from the upper atmosphere above the shadow zone), the bright horizon turns red (analogous to the reddened setting sun) and the zenith, blue. Measurements of the zenith polarization show beautifully the diffusion of multiple scattering—the zenith polarization drops almost to zero during totality (see Fig. 10).22

External

Viewed from above, the scattering by atmospheric gas and haze is often complicated by light scattered by the background surface. But this external geometry is ideal for studies of optically thick clouds, using meteorological optics to infer cloud-particle microstructure. Much of this issue is devoted to rainbows, glories, halos, arcs, pillars, circles, parhelia, subsuns, etc. I will limit myself to one rather powerful technique and then proceed to discuss measurements of the global Earth.

If you fly above the clouds, it is possible to measure a phase function for a specific cloud within a few minutes by scanning your line of sight from forward, through the nadir, to the rear. This usually requires a modification of, or attachment to, the aircraft.23 Figure 11 shows simultaneous measurements of intensity and polarization while flying over maritime altostratus clouds, as a function of phase angle (the angle measured at the scatterer, between the directions to the source and to the observer; thus, phase angle = 180° − scattering angle; at 0° phase angle the observer is looking down, exactly along the antisolar direction). The intensity increases for forward scattering, but shows no specific diagnostic features. The linear polarization, however, shows a strong primary cloudbow and a supernumerary bow. Thus we are dealing with spherical droplets, and can determine their effective radius (and, in fact, a measure of the width of the size distribution) by computing an array of models using multiple Mie scattering.
and the known refractive index of water. Figure 11 illustrates the dependence on particle radius, using the best fits for effective width (i.e., the effective variance, a dimensionless number approximately equal to the square of the standard deviation expressed as a fraction of the mean radius) of the distribution of radii (1/40) and for optical depth of the cloud (8). The effective radius is (14 ± 3) μm, and the quantitative fit to the observations is excellent. The choice of an infrared wavelength of observation (to minimize Rayleigh scattering by the gas, and to bring the wavelength closer to the expected particle sizes) is not necessary here; cloudbows and the structure of the polarization phase function would be seen similarly at visible wavelengths.

We can understand the greater importance of the degree of linear polarization rather than the intensity as a diagnostic
FIG. 14. Polarization of the "earthshine" reflected back to the Earth by the Moon. The dark side of the Moon serves as a depolarizing "mirror" in which we view ourselves, providing a complete phase curve of the global Earth every 14 days. The polarization measurements of Dollfus\(^{(2)}\) (•) have been multiplied by 3.5 to correct for depolarization by the lunar surface. In addition are shown recent measurements of the global Earth from the Voyager\(^{(1)}\) (O) and Pioneer Venus Orbiter\(^{(2)}\) (+) space probes.

Tool by looking at model calculations as a function of cloud optical depth. Figure 12 shows computations by Hansen\(^{(25)}\) for the sun overhead, looking from the nadir to the horizon, at a cloud of spherical particles. For optical depth 1/4, single scattering dominates. The intensity is low, but structured, showing cloudbow and glory features, with a maximum "contrast" of about a factor of 2. For this thin cloud, the polarization will have a maximum in the primary cloudbow of \(-65\%\) and additional structure due to the glory. It is significant to note that for such small particles the maxima and minima of intensity and polarization do not occur at the same scattering angles, as they generally do for geometrical optics (cf. the rainbow from large water droplets). As the optical depth increases, multiple scattering accounts for a greater and greater portion of the reflected radiation. The total intensity shows a different angular structure, and the specific features remain barely discernible. Meanwhile, the degree of linear polarization (whether positive or negative) decreases owing to dilution by the multiply-scattered light, but the structural details remain. In particular, the points of zero polarization are preserved, and thus can serve to characterize the single scattering, regardless of the optical depth and its variations. The intensity, of course, will always fluctuate in direct response to optical-depth changes.

One more example shows the polarization as diagnostic of particle shape. Figure 13 shows measurements on a thick altocumulus layer, and on an extensive, optically thick (approximately 5000 m thick) cirrus deck associated with the Intertropical Convergence Zone, north of Surinam. Note the lack of cloudbows and glory structure for these ice crystals, the predominant positive polarization, and the negative branches. We cannot yet compute phase functions for crystals, but the lack of features unique to a circular cross section is obvious. From Earth orbit we should be able to map the particle shape, and the size of liquid droplets, in terrestrial cloud tops.

FIG. 15. Surveyor III photographs of the Earth eclipsing the sun. One image is shown nested within the other. The refraction halo contains a number of bright beads, which correlate well with cloud-free regions on the Earth's limb (after Shoemaker \textit{et al.}\(^{(26)}\)).

FIG. 16. Phase curve of global Venus. The brightness is expressed in astronomical magnitudes after normalization to standard Sun-Venus and Earth-Venus distances. Observations made from the earth are compared with four cloud-model calculations (after Arking and Potter\(^{(31)}\)).
Rising higher, the Skylab astronauts have photographed the high-altitude aerosol layers indicated in Figs. 5, 8, 9, and Plate 111.

Further away we see almost a hemisphere, and can study the Earth as a planet, relating it to our studies of Venus, Mars, Jupiter, Saturn, Titan, Uranus, and Neptune. Dollfus considered earthshine, with the dark (i.e., night) portion of the Moon serving as a probe of the light scattered by the Earth. Seen from the Moon, the global Earth undergoes a full range of phase angles every 14 days. The Moon backscatters some of this earthlight back to us on Earth; since it is back-

FIG. 17. Synthesis of ground-based observations of the polarization of sunlight reflected by Venus. The mean variation of the percent linear polarization is shown as a function of phase angle $V$ and wavelength $\lambda$. The complex structure is fully understood in terms of molecular scattering plus multiple scattering by a cloud of spherical droplets (after Dollfus and Coffeen).

FIG. 18. Calculations of percent polarization for single scattering of unpolarized incident light by spheres of (real) refractive index 1.40. On the left are the wild fluctuations in polarization (black is positive polarization, implying electric vector vibration perpendicular to the plane of scattering; white is negative, implying parallel) for a single particle of radius $a$. On the right are the same data but for a relatively narrow size distribution (effective variance $= b = 0.01$) having mean effective radius $= a$. Note that the integration over size eliminates the detailed interference patterns, revealing the features of cloudbow, glory, etc. (after Hansen and Travis).
scattered (i.e., 0° phase angle), the irregular lunar surface cannot polarize this light; it can only depolarize it. Based on measurements of laboratory samples, this depolarization is considerable; all measured polarizations of the backsattered earthshine must be multiplied by 3.5. Figure 14 results; the shape of the curve is more certain than the absolute vertical scale. Note the lack of specific features (cloudbow, etc.). The shape is generally similar to that for scattering by molecules, soil surfaces, snow, ocean, and/or cirrus clouds. Actually, a major component, particularly at large phase angles, may be sunglint off the ocean and cloudtops. Recently the Voyager 1 Photopolarimeter Subsystem measured the linear polarization of the Earth at a 107°.3 phase angle, and the Pioneer Venus Orbiter Cloud Photopolarimeter has observed the Earth at several phase angles en route to Venus. These data are included in Fig. 14, interpolated to an assumed scotopic wavelength of 507 nm.

Scattering by our atmosphere can be probed externally by other means, including lunar eclipses, and the rather neglected use of artificial Earth satellites as probes of the Earth shadow. One of the most intriguing observations is the photography by Surveyor of the Earth eclipsing the sun, reproduced as Fig. 15. The brightest region is that nearest the sun, and moves with time. The rest of the bright features in the refection halo (indicated in Fig. 15 by letters and the corresponding terrestrial latitudes of the points on the limb) are stationary, and are correlated with cloud-free regions on the limb. This photo shows explicitly the light source that illuminates the Moon during a lunar eclipse.

VENUS

Most of our data on Venus have been obtained externally by remote sensing from the Earth or from fly-by spacecraft. Visually the planet appears bright and featureless. Deducing the nature of this bright atmosphere, whether gas, haze, or clouds, is a beautiful application of meteorological optics, the key being the discovery of a cloudbow on Venus.

Venus can be observed over a full range of phase angles (sun-Venus-observer angle), from the Earth, in ~292 d. Measurements of the global brightness of Venus vs wavelength and phase angle show a smooth variation, distinguished by absorption in the blue and ultraviolet and high reflectance in the yellow and red, the yellow color becoming more saturated as the phase angle decreases. The shape of the phase curve (see Fig. 16 and Fig. 3) and the change of color with phase are evidence for a multiple-scattering medium containing large forward scattering particles.

The global linear polarization of light scattered by Venus has been measured over a wide range of wavelengths and phase angles, and shows much more structure than does the intensity. Figure 17 is a synthesis of all the polarization observations. The amount of detail is remarkable, and repeats almost exactly from year to year. The pattern for a thick Rayleigh atmosphere would be very simple, with large positive polarization near 90° phase angle, decreasing for smaller and larger angles, and similar at all wavelengths. The details in Fig. 17 are attributed to scattering by particles in the atmosphere; the sharp peak of positive polarization at small phase angles in the violet is identified as a cloudbow from spherical particles.

For spheres we can generate realistic cloud models using the exact Mie theory for any size distribution, any refractive index, and any optical depth. Figure 18 shows single scattering computations of linear polarization for a single spherical particle as a function of wavelength and phase angle. The polarization fluctuates wildly, even changing sign for a small change in wavelength (or size) or angle, the result of detailed interferences between reflected, refracted, diffracted, and surface rays. Integrating over any realistic size distribution, however, immediately smooths the diagram to reveal the features of cloudbow, glory, anomalous diffraction, etc. (see Fig. 18). Increasing the width of the distribution causes further smoothing, but does not change the general pattern, as shown by Hansen and Travis. Changing the refractive index causes the features to move, but most important is that the evolution of the structure in this diagram can be followed continuously over the entire range of refractive indices (real as well as complex), as shown by Coffeen.

The polarization, as a function of wavelength and phase angle, was computed for all significantly different combinations of refractive index and particle size of spheres. This excluded all but a narrow range of candidates for the Venus clouds. A quantitative fitting with observations then required accurate calculations of multiple scattering, which led to a very tight constraint on the particle properties: refractive index \( n = 1.46 \pm 0.02 \) at 0.365 \( \mu \)m decreasing to 1.43 ± 0.02 at 0.99 \( \mu \)m, mean particle radius 1.06 ± 0.1 \( \mu \)m, effective variance of the size distribution 0.07 ± 0.02 (see Hansen and Hovenier). If we refer to Fig. 17, the positive polarization peak in the violet at 18° phase angle is indeed the cloudbow, the
Three other Venus observations should be mentioned in a discussion of meteorological optics. The dark (night) side of Venus is repeatedly claimed to be visible from the earth. This ashen light could be earthshine, as suggested by Napier, airglow emission, or even a glow from chemical reactions in the lower atmosphere or surface. Secondly, two images of the

negative polarization in the red at \(~15^\circ\) phase angle is a glory feature (broad at this wavelength because of the small value of the size parameter), and the positive polarization peak in the green at \(160^\circ\) phase angle is generated by "anomalous diffraction" interference.

Only one feature, the positive peak in the violet at \(80^\circ\) phase angle, is missing from the theoretical model. This feature is explained by a small amount of Rayleigh scattering in and above the cloud tops. Figure 19 shows the observations at 0.365-\(\mu\)m wavelength, with calculations for a mixture of cloud particles (parameters as specified above) and Rayleigh scatterers. The resulting gas pressure at the level of unit total optical depth is \(~50\) mbar. This pressure, averaged over the Venus disk, shows long-term variations from 25–60 mbar, suggesting global changes in the mean cloud-top altitude, in the planetary albedo, or in the mean free path of photons in the cloud.

The most likely candidate for the Venus cloud particles, having the right refractive indices, and which could exist in droplet form at the 50-mbar level, is an aqueous solution of sulfuric acid \(~75\%\) \(\text{H}_2\text{SO}_4\) by weight. Thus from quantitative measurements of the Venus meteorological optics and complete model-atmosphere calculations, we have deduced a basic description of the cloud particles and their probable composition. The next step will be the detailed mapping of scattering properties, using a photometer/polarimeter on the Pioneer Venus Orbiter spacecraft, which entered Venus orbit on 4 December 1978 (orbital period 24 h, inclination 75°, pericenter altitude 200 km, apocenter 66 000 km). Images of Venus at wavelengths shorter than 390 nm show much structure, with contrasts exceeding 30%, and daily variations (see Fig. 20). Understanding these brightness variations is a principal goal of the orbiting polarimeter experiment.

FIG. 21. Jupiter measurements along a north-south scan line at \(103^\circ\) phase angle taken by the Imaging Photopolarimeter on Pioneer 10. Illustrated are, starting from the bottom, the intensity at 440 nm, the color ratio (440/640), the percent linear polarization, and the direction of maximum vibration. The scan crossed various belts and zones as indicated. Note the Red Spot which is dark in the blue, the very large polarizations found at the limbs, the variability of \(P\) along the scan, and the uniformity of \(\theta\) (after Coffeen).
Venus surface have been obtained by the Venera 9 and 10 landers. In spite of the thick atmosphere [optical depth at 550 nm ≈ 17 (gas) + 35 (clouds) = 52], the illumination is adequate, and shadows are seen below the edges of surface rocks. Perhaps this is not surprising considering the high albedo of the haze particles and the low albedo of the surface. The zenith will be the brightest point in the overcast Venus sky, thus forming diffuse shadows. Finally, unobserved but predicted is the superrefraction of the Venus atmosphere. Below 12 km altitude the radius of curvature of a light ray is less than the radius of a surface of constant pressure. An observer on the surface would seem to stand in the center of a great depression, with the horizon elevated ~4° above the local horizon.

**JUPITER**

Plate 112 shows an image of Jupiter taken by the Imaging Photopolarimeter on Pioneer 11. Everywhere are clouds—several different species judging by the color differences. It was possible to measure the polarization of Jupiter (more correctly, the global linear polarization of sunlight scattered by the Jupiter atmosphere) at a wavelength of 440 nm over a range of phase angles during the interplanetary trajectories of Pioneers 10 and 11. The data thus far indicate a curve similar to that for the Earth shown in Fig. 14, but with a polarization maximum of ~15% at ~105° phase angle.

There is no direct evidence of spherical particles (cloudbows, glory, etc.). Frozen particles are predicted at the cloud tops; a search for halos, as evidence of dihedral angles in crystals, will be undertaken with photometer/polarimeters on the Voyager and Galileo spacecraft.

Intensity and polarization were mapped over the Jupiter disk during the Pioneer encounters. Strong evidence of Rayleigh scattering was found, the polarization reaching a remarkable maximum of 72% at 98° phase angle at the pole (where a maximum is expected due to the geometry of grazing incidence and grazing emergence, which maximizes the intensity ratio of single to multiple scattering).

Typical data are shown in Fig. 21, giving the intensity, color, degree of linear polarization, and direction of vibration on a north-south scan line. If we attribute the polarization in the blue entirely to (multiple) Rayleigh scattering by gas above clouds that are assumed to be Lambertian (the zero-order model), the observed intensity and polarization at each point are inverted, using the particular scattering geometry at that point, to yield the Lambert reflectivity of the clouds, and the vertical optical depth of gas above the clouds. This optical depth is converted to the corresponding atmospheric pressure, which, using the best available temperature structure of the atmosphere to specify the scale height at each height, is converted into relative altitudes of the cloud tops, shown in Fig. 22. Thus, the polarization of Jupiter's skylight gives us the cloud topography. The absolute heights are somewhat model dependent, but the relative variation is known. A more complex model, compared with data taken at several phase and zenith angles, will place limits on the vertical layering of the clouds.

**SUMMARY AND FUTURE**

We look and we see light reflected from an atmosphere. We see all the light that was not absorbed; we see the result of all orders of scattering. The unique geometry of single scattering is lost in the higher-order scatterings, and the total intensity best represents the total optical depth. The features of single scattering are usually lost; the rainbow is, of course, seen well outdoors, but usually against a dark background that limits the intensity from multiple scattering. The degree of linear polarization, often highly structured in single scattering, is diluted but rarely distorted when we see the net effect of all scatterings. For example, just before sunset, if there are bright clouds in the east, 30°-40° above the horizon, you will often find them to show considerable polarization (by rotating a simple polarizer in front of your eyes). This is a cloudbow, not discernable as an intensity enhancement, but striking as a polarization enhancement. A corollary to this behavior of linear polarization is that the direction of vibration is nearly invariant to the optical depth, so the neutral points of single scattering will be preserved. These rules fail when we look at transmitted light, with the atmosphere interposed between us and the sun, for here the single scatterings are lost to us by reflection as the optical depth increases.

Finally, we come to the circular polarization, which has been neglected by almost everyone in meteorological optics. Yet it offers a unique tool for separating some of the variables. Neither single nor multiple scattering by a gas, even when illuminated by linearly polarized light, can generate circular polarization. But scattering by larger particles generally does produce circular polarization, provided linear polarization has been created in the scattering process. Thus, circular polarization arises when aerosols are illuminated by a linearly polarized searchlight beam (used to detect aerosols in our atmosphere), or when aerosols or clouds, illuminated by unpolarized light, are sufficiently thick to ensure multiple scattering. (Thus, circular polarization has been detected on Jupiter, and Mie computations predict its presence.)
Circular polarization should be exploited in the detection and analysis of aerosols!

I would like to suggest four other productive directions for the future in meteorological optics:

(i) The process of twilight is so complex that its understanding can tell us, twice daily, countless details of the vertical and horizontal structure of the immediate atmospheric conditions. The greatest need here is for a realistic three-dimensional computer model.

(ii) Lasers are opening new areas in meteorological optics, particularly in the analysis of single-particle scattering and in the detection of aerosol layers. We can expect a rapid evolution of the methods of remote sensing, as active techniques supplement and supersede passive techniques.

(iii) Other planets and satellites have turbid atmospheres. We lack even the most basic description of their meteorology, cloud species, cloud structure, etc. Meteorological optics may well be the key, as the discovery of a cloudbow on Venus led directly to the deduction of the chemical composition of the clouds, when fly-by and even penetrating, sampling spacecraft could not do so.

(iv) Related to the above is the need for polarization and brightness phase functions for crystals and irregular particles. What halo(s) is (are) expected for frozen ammonia crystals? What even is the shape of a methane snowflake?

ACKNOWLEDGMENTS

This paper was an invited review presented at the Topical Meeting on Meteorological Optics, Keystone, Colorado, 28 August 1978. I would like to thank the organizers of the OSA Topical Meeting on Meteorological Optics for their encouragement of this work and for achieving a most stimulating and exciting two-day immersion in meteorological optics. I also thank Dr. L. Travis for his advice on various light scattering problems.


4W. J. Humphreys, Physics of the Air (Franklin Institute, Philadelphia, 1920).


35See Figure 17 in D. L. Coffeen and J. E. Hansen, “Polarization Studies of Planetary Atmospheres,” in Planets, Stars and Nebulae Studied with Photopolarimetry, edited by T. Gehrels (University of Arizona, Tucson, 1974).

36It should be noted that the Venus particles form more of a “haze” than a “cloud.” K. Kawabata and J. E. Hansen ["Interpretation of the Variation of Polarization over the Disk of Venus," J. Atmos. Sci. 32, 1133–1139 (1975)] deduce a photon mean free path of ~5 km at the level where the vertical cloud optical depth is unity, compared to a mean free path of ~0.1 km in typical terrestrial clouds.

Visual observations from space

Owen K. Garriott
NASA Johnson Space Center, Houston, Texas 77058

(Received 10 October 1978)

Visual observations from space reveal a number of fascinating natural phenomena of interest to meteorologists and aeronomists, such as aurorae, airglow, aerosol layers, lightning, and atmospheric refraction effects. Other man-made radiation, including city lights and laser beacons, are also of considerable interest. Of course, the most widely used space observations are of the large-scale weather systems viewed each day by millions of people on their local television. From lower altitudes than the geostationary meteorological satellite orbits, obliques and overlapping stereo views are possible, allow height information to be obtained directly, often a key element in the use of the photographs for research purposes. However, this note will discuss only the less common observations mentioned at the beginning of this paragraph.

AURORAE AND AIRGLOW

A number of auroral photographs were taken from Skylab in early September, 1973, following a period of high solar flare activity. The Skylab orbit was nearly circular at an altitude of about 435 km and an inclination of 50°. The plane of the orbit in early September was such that Skylab passed through high southerly latitudes near local midnight, providing a good opportunity for observation and photography of the southern aurora. Figures 1 and 2 were taken on 11 September 1973, at about 1843 and 1844 UT, and show the same long auroral arc from two different perspectives.

These photographs were taken by this author with a hand-held 35-mm Nikon camera, using a 55-mm lens and exposure durations estimated to be 1–4 s. The photographs were made through a small window in a darkened area of Skylab by bracing one edge of the camera lens against the window and slowly squeezing and holding the shutter release mechanism. A small amount of image jitter is visible. Initial interpretation of these photographs has been made by Packer and Packer. From the star images visible on each print and the location of the horizon (coupled with the known Skylab orbit) they have established the time and approximate location at which each photograph was made. They have used densitometry to estimate the brightness of the auroral forms which often appear in excess of several hundred kilorayleighs.

Airglow is almost always visible at night and is readily distinguished from the less frequent auroral emission by both its color and altitude. Plate 113 is perhaps the best example of both auroral and normal airglow emission with good altitude determination. [This is Fig. 9 in Ref. 1.] The photograph was taken on 11 September 1973, at 2325 UT near local sunrise. Sunlight is scattered in the lower atmosphere, which defines the true horizon reasonably well at the lower edge of a narrow orange band at the earth’s limb. The normal airglow layer appears orange to brown in color and at an altitude of 78–84 km above the earth. The diffuse auroral emission is measured to be in the altitude range of 94–105 km and appears brighter and greenish white in color.

These altitudes are obtained by direct measurement from the photographic print, with scale established by the star angle difference between υ Hydrae and δ Crateris, which are both visible on the prints. An additional 2 km is added to the apparent altitude to account for displacement of the visible