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OPTICAL PHENOMENA IN PLANETARY METEOROLOGY

by

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It has recently been suggested by Professor John D. Isaacs, of the Scripps Institution of Oceanography, University of California, San Diego, that significant information concerning the atmospheres of Venus, Mars, and Jupiter might be wrested from terrestrial observation of their anti-corona, halo, and rainbow phenomena. This report is a compilation, in the form of an annotated bibliography, of available information concerning what is now known of planetary atmospheres, pertinent optical phenomena in terrestrial meteorology, and the means for acquisition of further data concerning terrestrial and extra-terrestrial atmospheres.

In its outline of a general approach to planetary atmospheric research, the National Research Council Committee on Atmospheric Sciences (NRS-1962) states:

> "Firstly, it is cheaper to make an observation from the earth, or from a balloon, than it is from a space vehicle. Therefore, during the early phase, every effort should be made to gain knowledge with the aid of suitable terrestrial observations." (Vol. 1, Section 3.4.1)
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> "As observations become available, there will develop an increasing need for experimental and theoretical studies of physical as well as dynamical phenomena and for comparisons with results gained from research on our own atmosphere." (Vol. 1, Section 3.4.4)

Thus the potential value of further thought and research along these lines is recognized. The phenomena under consideration are in the visible "window" of our atmosphere, and are subject to search by means of existing astronomical techniques. That they have not been observed heretofore is perhaps because they have not been sought.

Individual "fly-by" experiments and space probes concern themselves with only a single planet and must be launched at carefully specified times. A search of optical phenomena would have to be conducted at specified times --for particular phase angles -- but these would be more frequent, and could be applied at once to all celestial bodies of interest.

I. PLANETARY ATMOSPHERES

The basis for modern theories concerning the atmospheres of the planets goes back to the classic article by Jeans (1941), in which he derived equations for the probability of gravitational escape of thermally excited gas molecules. Kuiper (1950, 1952) has noted that such calculations depend upon the (unknown) temperature of the uppermost atmospheric layers rather than surface temperature. Firstoff (1959) has pointed out other factors not considered by Jeans, and Urey (1952, 1959) has contributed to the discussion.

Planets are supposed to have condensed with more or less "cosmic abundance" values of the chemical elements and to have become fractionated, with formation of a primitive atmosphere composed of thermodynamically stable molecules, principally hydrogen, helium, methane, ammonia, water, neon, and argon. Solar and meteorological attrition of these molecules will temporarily dissociate them at higher levels and will result in a steady-state Boltzmann distribution of high-temperature light element atoms. Their r.m.s. velocity will be

$$\bar{v} = (3kT/m)^{1/2}$$

(where k = Boltzmann's constant T = absolute temperature, m = atomic mass) Planetary escape velocity,

$$v = (2GM/R)^{1/2}$$

(where G = gravitational constant, M = mass of planet, R = radius of planet to atmospheric layers where the mean free path is large) will be achieved by the most energetic of these atoms in inverse root proportion to their mass. Over a period of the order of 10^{10} years the major solar planets (small T, large M/R) would be expected to have lost some hydrogen and helium (small m), but little else -- and to date this loss may have been negated by accretion. Earth, Venus, and to a certain extent Mars are of a size and solar distance that most of the hydrogen and helium have been lost, but other gases have been largely retained. Mercury, Pluto, and the several satellites are too small to have retained any appreciable atmosphere.* The earth is the only anomaly to the expected order of atmospheres in the solar

* Herzberg (1951) has reported observation of methane on Titan, satellite of Saturn and largest of all solar system satellites.

system. Earth has an additional source of atmospheric loss: Carbohydrate based organisms have here removed carbon dioxide (M.W. 44) from the atmosphere and stored it, principally as non-volatile carbonate. The net result is that Earth has less atmospheric cover than its smaller and warmer neighbor, Venus.

Mercury is considered to have no true atmosphere. Its small mass and high temperatures on surfaces exposed to the sun (up to 400°C) provide the combination of high gas molecule velocity and low escape velocity (3.6 km/sec). High energy radiation from the sun dissociates its surface into smaller molecules which have appreciable vapor pressure and appreciable probability of escape. It is likely that the planet is slowly subliming to nothingness.

Dollfus (1957), from polarization studies, has concluded that Mercury has an atmosphere of about 1 mm Hg. Evidence has been obtained for the occurrence of faint and very volatile clouds, which are attributed to dust storms.

Venus has no resolved surface features, from which it is inferred that it has perpetual and total cloud cover. Terrestrial determination of the chemical composition of these clouds is hampered by the absorption of our own atmosphere. If optical phenomena associated with a localized meteorological disturbance were observable in some way, the rotation period of Venus could be studied in the same fashion as we now observe sunspots.

Kuiper (1954 A) observed three bands in the southern half of the disc which reflected ultra-violet light. On the assumption that these were parallel to the equator its obliqueness was thus measured as about 32°. Rapid rotation of the planet is implied. Kraus (1956) observed a periodicity of radio emission from the planet (attributed to its rotation) of slightly less than one day. Gusev (1958) reported observation of rotation of a north polar cap in 22 hours 30 minutes. Link (1959) observed an aureole during transit of Venus across the Sun which would result from refraction of about 0.1 atmosphere. Asymmetry of the aureole was taken as evidence of polar regions. Rubashew (1950) used light filters to observe non-uniformity of the cloud cover. From such non-uniformities Kuimov (1958) measured its rotation period as 20 to 35 days. Goldstein and Carpenter (1963) used Doppler radar to establish a rotation period of 250 $\pm$ 40 days retrograde. (225 days retrograde is no rotation at all in Venusian coordinates.) For their calculation one important assumption is that there is no axial tilt.

The yellowness of the planet has been accounted for as upwelling dust cluds, polymerized carbon-suboxide hydrate clouds, or as formaldehyde clouds, as well as condensed CO_2, NO, O_2, or H_2O. (Cf. Whipple (1958) and Menzel and Whipple (1955). Evidence for diffusion of light in its atmosphere is described by Link (1957), based on lengthening of the cusps. The surface temperature on Venus has been "measured" at various values -- from 0° to 300° C at the equator, and down to -200° C at the poles. Clearly, there are no flawless data and there have been many conjectures concerning the nature of the atmosphere of Venus.

Mariner II, the Venus "fly-by" experiment, yielded the following during "encounter" at 2000Z December 14, 1962 at which time the probe was 4100 km from the center of the planet:

1. Frank, Van Allen, and Hills (1963) found no charged particle flux ($\geq$ 40 kev e^- or $\geq$ 500 kev H^+) and conclude that the magnetic dipole of Venus is less than 0.18 that of Earth.

2. A magnetometer sensitive to 4×10^{-5} gauss detected no field at this distance. (Smith, Davis, Coleman, and Sonett, 1963).

3. Microwave observations at 19 mm wavelength suggest that the source is beneath clouds. It is assumed that this is the surface of the planet. To within an estimated uncertainty of $\pm$ 15%, measured source temperatures were 460°, 570°, and 400° K for dark side, near the terminator, and light side, respectively. Measurements at 13.5 mm wavelength were made also. (Lilley and Barrett, 1963).

4. Infra-red radiometry in the 10.2 - 10.5 μ CO_2 band and in the 8.1 - 8.7 μ window indicates little CO_2 abosrption in the light path. Chase, Kaplan, and Neugebauer (1963) conclude that their temperature measurements are therefore those of the upper regions of thick clouds. They measured 240° K with a 20° limb-darkening. A cool spot was observed in the southern hemisphere which they speculate may have been the result of locally higher or more opaque clouds or a planetary surface feature.

Sporadic loss of definition of the surface features of various areas of Mars has been interpreted as being caused by clouds. Observation of these storms leads to the conclusion that the planet has a horizontal distribution of temperature and winds comparable to those of Earth, were its mean temperature -23° C, mean warmest temperature -8° C, and atmospheric pressure 37 mm Hg. Yellow clouds are most prevalent at perihelion and white clouds at aphelion. Dollfus (1948), from polarimetric studies, concludes that the white clouds are ice crystals, that the blue haze is similar to Earthian mother-of-pearl clouds, and that the mean atmospheric pressure is 6 cm Hg. The dark fringes he observes on the polar caps in spring are probably liquid water. Hess (1958) notes that the blue haze is probably a condensate rather than dust, because it may be observed to clear away quite rapidly. Urey (1958) suggests, instead, that the haze is the result of fluorescing molecules in the upper atmosphere of Mars. This might be no less thought-provoking than Shklovskii's suggestion (Cf. Guerin, 1959), based on the extraordinary angular acceleration of Phobos, that the Martian satellites are artificial and were launched approximately two billion years ago.

Concerning atmospheric optical phenomena, which would be manifest as brightness and color changes as functions of phase angle, Dluzhnevskaia (1960) has used brightness contrasts at opposition to investigate turbidity, thought to be related to dust storms. Sharonov (1960) notes a correlation between color and phase for Mars. Kovel (1957, 1959) observed that the slope of brightness distribution curves in the spectral region 560-660 nm decreases with increasing meridian altitude of the Sun. Near opposition, there is little difference between color of the maria and continents. Maria at low southern latitudes change color with variation of meridian altitude of the Sun. Reflection from maria does not follow Lambert's law. Atmosphere over the maria is more transparent than over continents. The south polar cap seems more reddish than the north polar cap.

Jupiter and the other major planets, Saturn, Uranus, and Neptune, are of sufficient mass and sufficient distance from the sun -- so at low temperature -- that the opposite combination from that on Mercury has prevailed. Little of even the lightest element, hydrogen, has escaped, so the atmospheres are of a reducing nature. Ammonia and methane predominate. It is interesting to speculate on the possibility of observing an ammonia rainbow, or on the determination of the crystal form of Jovian meteorological ammonia ice by observation of ice halos and parhelia.

Mars is generally thought to have an atmosphere consisting principally of nitrogen, with small amounts of argon, oxygen, water vapor, and carbon dioxide. It lies beyond the Earth's orbit, so might be subjected to study of anti-corona phenomena. Because of its distance from the sun (low temperatures), it would seem subject to study of halo phenomena, which on Earth are caused by ice crystals.

The bands of Jupiter are thought to be created by terminations of Van Allen type belts and the resultant formation of colored free radicals trapped in solid methane or ammonia matrices. The variation of rotation period with latitude is construed to be evidence that the bands are not stationary with respect to a solid surface. Its mass and hydrogen content are thought to be close to the maximum without the possibility of a sustained thermonuclear reaction; Jupiter is a "maximum" planet. The red spot has been considered to be the result of atmospheric disturbance overlying a prominent, though invisible, surface feature.

Saturn has more methane and less ammonia than Jupiter (Whipple, 1958). Sharonov (1954) points out that photometry of Saturn's rings gives interesting data of their variation of brightness with inclination. The rings have been asserted to be ice crystals. Observation of halo phenomena could confirm this, although failure to observe halos would not destroy the hypothesis. (The maximum Sun-Saturn-Earth angle is 18^{o}, so that only a limited number of angles could be sought. Also, halos depend upon preferred orientations; it is not clear that there would be preferential directions in the rings.)

Bobrov (1959, 1960a, 1960b) has derived the theoretical phase functions of the brightness of Saturn's rings. Applied to the B ring, he finds good agreement with Schoenberg and Lebedinets (1929) observations. Seeliger's theory of shadow obscuration is found to be at variance with observational data. The B ring is too bright for diffraction theory.

Herzberg (1952) believes that helium is present on Uranus and Neptune in even larger amounts than hydrogen, three to one. He estimates the partial pressure of hydrogen at the bottom of the visible atmosphere as two atmospheres.

To complicate (or add to) the possibility of observation of special optical effects in planetary atmospheres, Becker (1933, 1948) has observed semi-regular, long-period fluctuations in the reflectivities of Saturn and other Jovian planets.

A variation of 0.3 magnitude with period 8.4 years was observed for Uranus. (Ashbrock, 1948). Stebbins and Jacobson (1928), however, observed no fluctuation -- instead, only a variation of 0.01 magnitude with phase angle from 0 to 2.5°.

Little is known about Pluto, except that its origin is probably different from that of the other outer plants. From albedo, its rotation period is about 6.4 days. Techniques under consideration for learning about its atmosphere are probably no better than current techniques, for the reason that so little light is reflected to Earth from its entire surface, let alone small variations due to small disturbances on the surface.

Concerning the asteroids and the Trojan planets, none are larger than 600 miles in diameter, so none can be expected to have retained gaseous materials despite the low temperatures associated with their distance from the sun.

Concerning satellites, only Titan (Saturn) has been reported as having shown the possibility of atmosphere -- methane. The Galilean satellites of Jupiter may, however, hold some future interest. The Moon is of special interest, because of proximity. But there is no evidence that the Moon has sufficient atmosphere to produce any of the effects of interest in the present context.

A possible complication to a study of planetary atmospheres by means of anti-solar phenomena-- itself of considerable interest-- is discussed by Isaacs and Tyler (1960) and concerns variations in reflectivity caused by unresolved surface features.

For a general survey of planetary atmospheres, the reader is referred to Kuiper (1950, 1952), Horak (1950), and to the reports of the Lowell Observatory project (1948-1951). For a thorough bibliography of the subject, to Volume 12 of Meteorological and Geoastrophysical Abstracts, pp. 1862-1897, 2061-2114 and 2282--2328, published in 1962.

II. OPTICAL PHENOMENA OF TERRESTRIAL METEOROLOGY

The optical phenomena which are considered in this section, are those which are thought to have value for the purpose at hand. Aurorae, extra-visible light, Rayleigh scattering, polarization phenomena, effects of Van Allen belts, mirages, visibility, green-flash, etc., are largely excluded. From the bibliography, also, are excluded, as far as is known, references to sightings of unusual optical phenomena without scientific discussion. The reader is referred to "Marine Observer" magazine for corroboration of unusual optical phenomena, mundane but calibrated halo angles, and assorted wierd observations, often with divine portent.

Anti-Coronae

The phenomenon of the anti-corona, also variously known as the glory, Brocken spectre, Brocken bow, fog bow, or cloud bow, consists of a shadow of the observer on clouds or mist, with the shadow of the eye of the observer surrounded by rings of vivid colors. It is generally accompanied by a true fog bow (or cloud bow) but is of different origin, only recently explained* (van de Hulst, 1947) and verified (Naik, 1954, 1955) on the basis of Mie scattering. Van de Hulst examined data collected by Pernter-Exner (1910) on natural clouds and by Mierdel (1919) on artificial clouds and reached the conclusion that anti-coronae are barely possible for mist droplets of refractive index 1.33, not possible for smaller index which would probably exclude ammonia droplets. Naik and Joshi prepared artificial clouds and observed the anti-corona by means of a convex mirror. The shadow (Brocken spectre) was seen as a reduced image surrounded by three to four orders of rings. The size of a ring of a particular color depends on the size of the droplets. The droplet size was measured by the apertures of the diffraction rings observed in transmitted light. For Brocken rings, $\alpha \sin \gamma_n = \pi(n - 1.22)$ where $\alpha = 2\pi r/\lambda$ and γ_n = angular aperture of the nth order bright ring. Bright rings were obtained only when droplet sizes were rather uniformly near 13.5 microns.

* The treatment has been extended by Mikirov (1958).

These observations are in satisfying agreement with the calculations of van de Hulst using Mie theory. The rarity of the natural occurence is thus understandable. Reports of ground observations have been limited to the Brocken, an area in the Hartz mountains of Saxony, the Desert View Watch Tower, Grand Canyon, Arizona, and the Hawaiian Islands. Aerial observations are much more frequent. One report, (Baratoux, 1954), describes the Brocken seen in a dust storm during a flight from Bagdad to Beirut. It would appear that there has been some confusion in the literature between anti-coronae and the heiligenschein or shadow obscuration as treated by Isaacs and Tyler (1960).

1.	Baratoux, 1954	Brocken-Bow (?) of dust storm, aerial observation
2.	Black, 1954	Observation, Grand Canyon
3.	Douglas, 1921	Observation, Airplane
4.	Flammarion, 1888	Observation, Balloon
5.	Kulinovskii, 1958	Observation, Airplane
6.	Kupetskii, 1959	Classification of Kulinovskii's observation as an anti-corona
7.	Meyer, 1956	Discussion
8.	Mierdel, 1919	Study of Artificial Clouds
9.	Minaert, 1954	Discussion; points out inadequacy of Ray's treatment, pp. 224, 259
10.	Naik, 1955	Study of Artificial Clouds
11.	Pernter-Exner, 1910	Discussion
12.	Ray, 1923	Explanation on basis of scattering
13.	Van de Hulst, 1947	Explanation, Mie theory.

Shadow Phenomena:

Half an hour after dawn, cast on short grass or clover still greyish-white from heavy dew, an observer's shadow appears to possess an aureole, called the Heiligenschein. The phenomenon has been known for a long time; when in the sixteenth century the painter Benvenuto Cellini had been "released from a well-deserved term of imprisonment" he noted in his autobiography that the halo miraculously appeared, as a sign of divine recognition of his genius; his closest friends were able to see it also (although they appear to have neglected to mention that they saw it about their own head instead, for the effect occurs only at the anti-solar point.) (Cf. Doncaster, 1913).

It is caused by total reflection from the dew, brightest where there is no shadow obscuration. A true Heiligenschein can be observed also on plants with farinaceous coatings of globular cells (von Lommel, 1874).

Shadow obscuration can be observed under favorable conditions without need for enhancement by total reflection (Minnaert, 1954, p. 230). The effect can be seen in light reflected from uniform fields of grass and is quite pronounced when seen from an airplane (Baratoux, 1954).

Application of shadow obscuration has been made to measurement of texture of Saturn's rings (Schoenberg, 1929; Sharanov, 1954; Bobrov, 1959, 1960) and to techniques for observation of unresolved planetary features (Isaacs and Tyler, 1960).

Other shadow phenomena: Meyer (1950) on double shadows; Ives (1945) on sunset shadow bands; Brocken spectre (vide infra).

Rainbows and Cloudbows:

Rainbows are the result of sunlight being refracted, totally reflected one or more times, and emerging near the angle of minimum deviation, from more or less spherical water droplets. For red light and for one internal reflection, this angle is $41^{\circ}20'$ for water spheres of radius larger than 0.03 mm. Two reflections produce the secondary bow, seen 51° from the anti-solar direction. Higher orders are exceedingly weak and probably cannot be observed naturally. (The tertiary and quaternary bows are in the direction of the Sun.) Diffractive effects alter the appearance of the bow; from this it is possible to estimate the approximate size of the drops from simple observation (Minnaert, 1954, p. 178):

$>$ 0.50 mm radius	Very bright rainbow, numerous supernumeraries
$\sim$ 0.25 mm	Red noticeably weak, fewer supernumeraries
$\sim$ 0.15 mm	Red missing, otherwise broad and well-developed. Supernumerary bows are yellowsih
$\sim$ 0.10 mm	Gap appears between supernumerary bows.
$\sim$ 0.08 mm	Gap between primary and first supernumerary.
$\sim$ 0.05 mm	Broad, pale primary, only the violet is vivid. Supernumerary is whitish.
$\sim$ 0.03 mm	Primary bow has a distinct white stripe.
$<$ 0.025 mm	Cloudbow.

Cloudbows or mistbows (Ulloa's rings, Bouguer's halo, etc.) are simply rainbows returned from small droplets. They are characteristically twice as broad as rainbows, white bands with unsaturated orange outer and blue inner rims. Frequently they are accompanied by supernumerary bows which may be vividly colored (red inner rim).

Their angular radius from the anti-solar axis may be several degrees less than 41°.

Descartes (1637) recognized the idea of minimum deviation and the origin of the rainbow in principle. Newton (1704) treated the rainbow more fully (Cf. Houstoun, 1930). Airy (1838) sucessfully treated the sigmoid nature of the emerging wavefront and accounted for the supernumerary bows. Pernter-Exner (1910) treated the full consequences of this in combination with diffraction effects.

Khan, however, attributes the first accurate explanation to Muhammad Ibn Mas'ud Ibn Muslip Qulb-Al-Din, born in 1236. (Cf. also Boyer, 1959).

Wiener (1910) calculated the angular distribution of radiation reflected and refracted by a spherical drop, Malkus (1955) has calculated the relative light intensity of rainbows and cloudbows as a function of the viewing angle, Volz (1960) notes that drops of radii larger than 0.2 - 0.5 mm are flattened and oscillating, so contribute little to the observed rainbow. Balaster (1951) has presented a thesis on rainbow and corona phenomena from the electromagnetic point of view. Shifrin and Rabinowich (1957) have calculated the spectral polarization of rainbows.

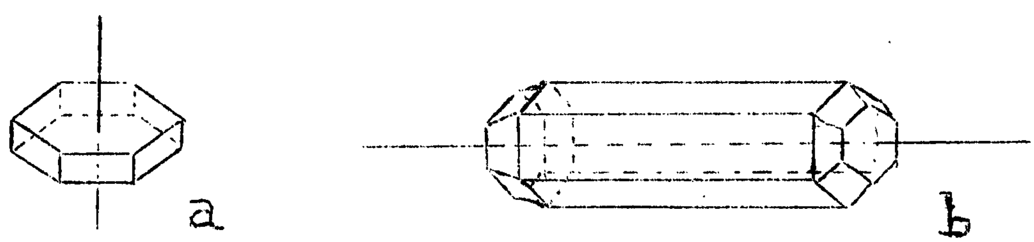
Tyndall (1883) and McConnel (1890) appear to have been the first to comprehend the nature of cloudbows.

<u>Halos and Parhelia:</u>

Small ice crystals falling through the air, under favorable conditions, can lead to elaborate displays of halo phenomena in which many of the following components may be seen:

1. Parhelia (or sun dogs or double suns) 22° from the sun.
2. Halo of 22°, red on the inside and white on the outside.
3. Arcs of Lowitz, vertical arcs of the 22° parhelia. Very rare.
4. Tangent Arcs of the 22° halo, portions of the circumscribed halo.
5. Parhelia of 46°.
6. Halo of 46°, fainter than the smaller circle.
7. Halo of Hevelius of 90° (Minnaert calls this dubious)
8. Antisolar halo of 44°
9. Antisolar halo of 38°
10. Circumzenithal Arc, relatively common, vividly colored horizontal rainbow.
11. Parry's Arc, small curved arc, just above the small halo. Rare.
12. Kern's Arc, the full circumzenithal arc.
13. Parhelic Circle. White, or red above near horizon.
14. Lateral Tangent Arcs to 46° halo
15. Infralateral Tangent Arcs of the 46° halo
16. Supralateral Tangent Arcs to the 46° halo
17. Anthelion, mock sun 180° from the sun on the parhelic circle. Rare.
18. Paranthelion, mock suns at 120° from the sun on the parhelic circle. Rarer.

All the above phenomena can be explained on the basis of reflection and refraction in ice crystals, which generally occur in one of two basic hexagonal forms:



In still air they will fall in the positions shown; these are the positions of maximum resistance. (Pernter-Exner's explanation (1910) did it backwards, according to Wood (1936). For the purpose at hand, only the most common and most vivid of the components need be considered, the 22° and 46° halos and their parhelia, the circumzenithal arc, and the parhelic circle. Alternate faces of both plates (a) and spicules (b) form 60° prisms, which transmit light at minimum deviation of 22° for the relative refractive index of ice. The 46° halo results from refraction through the 90° angles. A glass prism won't transmit through a 90° angle, but ice has a much lower refractive index than glass, and,if the position is just right a small amount of light does get through. Parhelia are simply bright spots on the halos, resulting from preferred orientations. The circumzenithal arc arises from refraction through the 90° faces of horizontal platelets. The parhelic circle is produced by reflection from the vertical faces.

Exceptionally complete halo displays have been recorded by Lacy et al (1954) and Shröder (1960), with photographs by Poncelet, Klinov, and Volz (1955), Liljequist (1956), and Kusin (1957), and from aircraft by Krylov (1952) and Singleton et al (1960).

Descartes (1637) correctly attributed the phenomena to ice crystals, and had the concept of minimum deviation (which he had applied to explanation of the rainbow), but two hundred years were required before Galle and Bravais (1847) were able to complete the basic description. Descartes' insight is the more remarkable if one compares his work with the authorities of fifty years previous. Heninger (1960) quotes Fulke's explanation of the halo (1571):

> "The Circle called 'Halon' is a garland of diverse collours that is seen about the Sunne, the Moone, or any other sterre . . . The matter wherein it is made, is a cloude of equall thicknes, or thinnes, comming directly under the body of the Sunn, the Moone, or other sterres, into whiche the lyght of the heavenly body is receyved, and so appeareth rounde, because the sterre is rounde."

and Hill's account (1571) of the origin of parhelia:

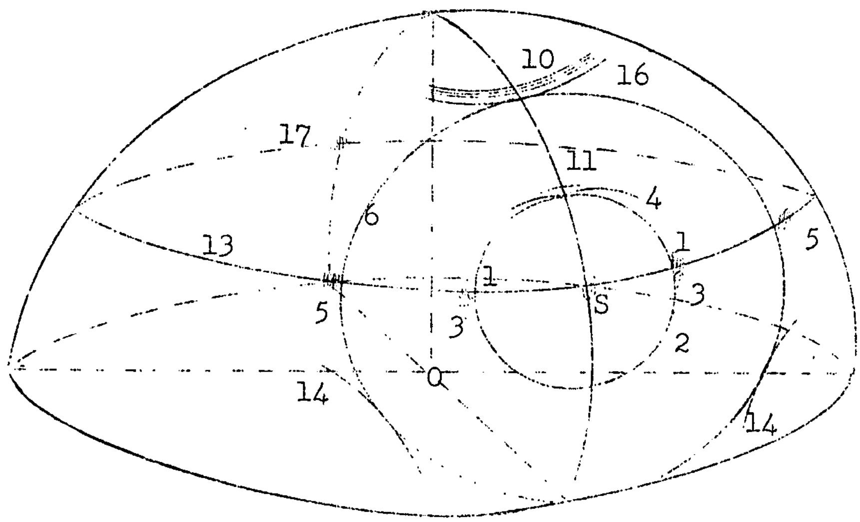
> "when a clowde of the one side of the Sunne, shall be placed eyther of the East, or West, especially equall, and a like thicke, which as a Glasse receaveth and expresseth the ymage of fygure of the sunne."

Archenhold (1933) produced an elaborate theory to account for his observed 27 day period of halo frequency. This was contradicted by Neuberger (1937), and Archenhold (1938) countered with an elaborate memoir. (Cf. Meteor. Abstracts)

A moderately dense distribution of the right kind of ice crystals over a continuous surface produces halos on the surface in those directions, point by point, at which they would appear in the sky if that were visible beyond the surface. Whitney (1893) and Renaud (1938) have observed the 22° and 46° halos on level snow surfaces as hyperbolae. Similar sightings are reported by Marquardt (1959) and Gabler (1954).

For a complete discussion of halo phenomena, reference should be made to Minnaert (1954, p. 190), Wood (1936, p. 388), Humphreys (1940, p. 501), or Woolard (1941). General descriptions are given by Volz (1956), Meyer (1957), HO (1959), by Visser (1956, 1957, 1959) and Maier (1950) on unusual aspects of the phenomenon, and by Humphreys (1923) on halos of unusual subtense.

Concerning artificially produced halo phenomena, see Alby (1953).



Location of halo phenomena. O. Observer; S. projection of sun; numbers refer to text on page 16.

Coronae and Aureoles:

Coronae are of frequent occurrence. They are rings around the luminary at variable distances, but generally closer than 22° and the red color appears on the outer rim (in contradistinction to halos). They result from diffraction by small water droplets. The smaller the drops the larger the corona. By Babinet's principle (The diffraction patterns of complementary diffraction screens are the same -- outside the projection of the aperture), they produce the same effects as small circular apertures of the same size. (Minnaert, 1954, p. 208; Wood, 1936, p. 388; Humphreys, 1940, p. 547.)

Verdet (1852) was the first to provide a satisfactory explanation. This has been expanded by Mecke (1921), and Isrardi (1920) has considered coronae produced by irregularly shaped colloidal particles (Bishop's ring is a faint reddish-brown corona caused by ~0.002 mm dust particles). Visser (1956) contends coronae may be caused by ice crystals as well. Haupt (1957) observed photometrically a simultaneous corona and halo.

Through very small fog droplets, vividly colored multiple coronae may sometimes be observed (Kohler, 1929). Simpson (1912) has accounted for iridescent clouds on the basis that these are fragments of coronae.

The occurrence of a corona is indicative of a great uniformity of particle size, hence of a freshly formed aerosol. Asymmetric coronae result from orderly arrangement of young cirro- or alto-cumulus clouds, with smaller droplets and larger corona radius toward the edges.

The diffraction disc at the center of the corona display is known as the aureole, although there is, in addition, a solar aureole caused by scattering.

Scattering Phenomena:

Superposed upon the preceding optical phenomena of the atmosphere are the effects of scattering and reflection of light by the atmosphere and surface. Rainbows, for example, are always seen in the foreground of the blue sky, as interrupted by clouds, which reflect illumination of the Earth's surface. Molecular scattering, aerosol scattering, and reflection are all represented.

Molecular scattering in planetary atmospheres has been treated by Horak (1950). Chandrasekhar (1950) has developed exact methods for obtaining some of the optical properties of diffusers, including the reflected intensity distribution for collimated light incident on semi-infinite diffusers scattering isotropically, Middleton (1941, 1950, 1954, 1960) has applied these to determination of the color of the overcast sky, based on the work of Schuster (1905), Mecke (1921), Dietzius (1923), Albrecht (1923), Moon (1940), and the observation of Moon and Spencer (1942) that a densely overcast sky is about three times as bright at zenith as at the horizon: Chromaticity and luminance are to a considerable extent a function of the reflectance of the ground, and depend only slightly on dissolved absorbing material in the cloud. The chromaticity of the upper cloud surface is not far from that of the incidentlight, especially for a heavy overcast.

Scattering by dielectrics has been treated by De Vore and Pfund (1947), and scattering by spherical particles by Sinclair (1947) and Theissing (1950). Van de Hulst (1946) and Houghton and Chalker (1949) discuss the scattering cross-section of water drops in air for visible light, following Mie theory.

Lander and Nielsen (1951) and Curcio (1960) have applied scattering theory to the determination of atmospheric aerosol particle size distribution, as have Kerker and Hampton (1953) using the polarization ratio. Curcio notes a bimodal distribution, which may vitiate estimates of size distribution based on attenuation of visibility only.

Scattering through fog and mist has been considered by Mecke (1921), Holmes and O'Brien (1932), Mili (1935), Middleton (1942), Eldridge and Johnson (1962), and from point sources by Richards (1956).

Visibility through atmospheric haze has been investigated by Hulburt (1941), Duntley et al (1948, 1955), Coleman and Rosenberger (1950), and Gibbons et al (1961, 1962).

Bennett and Nagel (1961) and Gehrels (1962) have noted a wavelength dependence of the polarization of the sunlit sky, which shows a maximum at 550 nm. Multiple scattering lowers it for the ultraviolet, ground reflection and emission lower it for the infrared. The latter is especially true if green plants are on the terrain.

Johnson et al (1939) measured the light scattered from a searchlight beam, to arrive at an estimate of the amount of ozone in the upper atmosphere.

Deirmendjian (1953-1958) has developed a quantitative theory of the solar aureole, and proposes that the brightness near the solar disc be monitored for purposes of detection of thermonuclear explosions.

Newkirk (1956) has studied the photometry of the solar aureole, concluding with the observation that investigation from an airplane of variation of aureole in various weather situations would allow determination of particle concentrations in three dimensions. Effects on the aureole of the jet stream and of more low-level phenomena could be separated by means of flights at 30,000 feet. Close surveillance would reveal any dependence upon solar corpuscular invasions.

The color of aureoles caused by scattering is dependent upon aerosol particle size. If this approaches the dominant wavelength of the source, the latter will appear reddish, because blue and violet are scattered out of the direct path. Cigarette smoke is blue when blown immediately into the air (reflected light) but is white if first held in the mouth. When this is done, the smoke particles become covered by a layer of adsorbed water and thus have larger and less uniform radii.

When a uniform cloud of dust particles of size in the range 0.001 to 0.005 mm is interposed between observer and sun or moon, the rare occurrence of a blue sun or blue moon is afforded. There was a blue moon on September 27, 1950, and a blue sun, caused by extensive forest fires in Canada, and seen throughout Canada, the northern United States, and Europe. (Angstrom, Bull, Chazy, Desseus, Jenne, Kraul, Penndorf, Rodewald, Sanson, Schieldrup-Paulsen, Steng, Wilson).

It is a popular belief that stars can be seen in the daytime from the bottom of a well. Smith (1955) could not confirm this. Taylor (1960) points out that the function of a well or chimney is probably that of a finder. His experiments showed no reduction in contrast threshold with restricted visual field.

Reflection:

The sub-sun phenomenon, seen from an airplane as an image of the

Sun reflected from a cloud, generally accompanied by aureole and corona, is caused by reflection from flat surfaces of quiescent floating ice-platelets of rather uniform size. (Minnaert, 1954, p. 203). The aureole and corona result from subsequent diffraction (Squire, 1952; Jacquinot and Squire, 1953).

Sun-pillars occur near sunrise or sunset, as vertical columns of light somewhat wider than the Sun and extending (rarely) as much as 15° above the Sun. They occasionally appear below the Sun as well. The most nearly satisfactory explanation is that they are caused by reflection from horizontal surfaces of ice-spicules rotating rapidly about a horizontal axis in their descent. (Minnaert, 1954, p. 201). Local enhancement of the brightness of a sun-pillar by unequal cloud distribution can produce the phenomenon of a double-sun. Poncelet (1955) has photographed a double-sun.

Gordon (1958) describes a green sun after sunset which he attributed to refraction, although it may have been a double-sun. The meteor was seen on the Isle of Skye; it might have been Drambouie.

To an extra-terrestrial observer, the phenomena of our atmosphere would appear to be modified by reflected light from the surface of the earth. Reflectance of daylight at the surface of the oceans has been considered by Powell and Clarke (1936), Stamm and Langel (1961), and Deirmendjian (1962). Reflection of light by water waves has been considered by Minnaert (1942). Van Wieringen (1947), and

Duntley (1951). Cox and Munk (1954) used sun-glitter in a method for measurement of sea roughness. The reflectivity of sand, snow, and other substances (Hulburt, 1928) and of desert terrain (Ashburn and Weldon, 1956) have been studied, and Middleton and Mungall (1952) and Christie (1953) measured the directional reflectivity of snow; here the angle of maximum reflectance appears to exceed the angle of incidence.

The influence of ground-reflected light on clouds has been investigated by Moon (1940) Nagel (1951), and Toolin and Stakutis (1958).

III. OBSERVATION OF OPTICAL PHENOMENA

Conditions are seldom right for observation of pertinent terrestrial optical phenomena from the surface of the earth. All the meteors considered are much more commonly seen during aerial observation - despite the fact that there are fewer observers aloft. While the coarse features of most of these phenomena are understood, the knowledge concerning them is by no means complete, and virtually no thought has been given to the story they might tell about what is going to happen meteorologically (beyond the popular belief that the number of stars contained within a halo around the moon is the number of days before a storm).

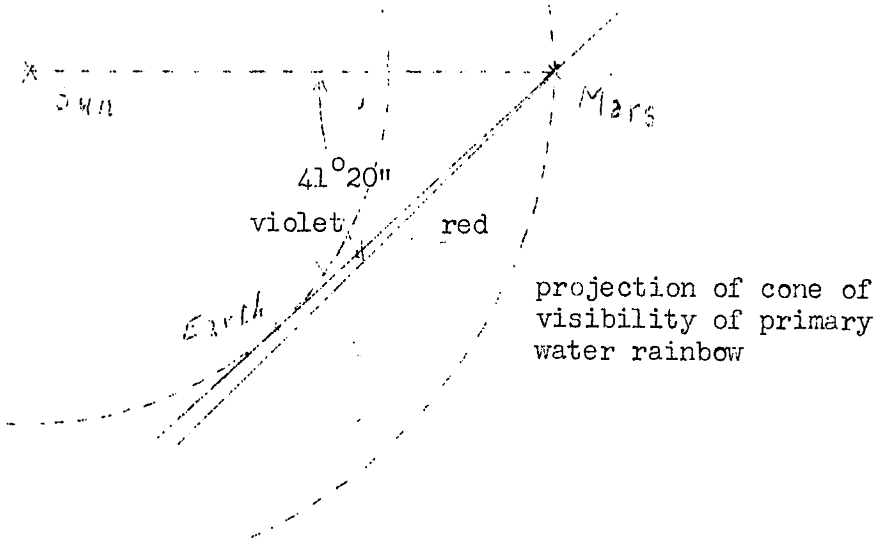
Aerial observations are less subject to disturbances from local terrain variations and can cover wider areas than ground-based studies. They have greater definition and control than is possible at present with weather satellites.

References to observations of optical phenomena from aircraft include Wiltberger (1939), Loewe (1940-1946), Packer and Lock (1951), Varley (1955), and Durst and Bull (1956). Specific references are citied individually in Part II.

Observation of the atmospheres of other planets would depend upon aerosol disturbances of a size which can be resolved by telescopic observation, or upon a collection of virtually identical disturbances of similar total size. (The same criteron can be applied to use of shadow obscuration phenomena for interpretation of surface irregularities.)

Refractive phenomena would be best observed spectrophotometrically. Relatively small differences in the total reflected light from the planet would need to be measured accurately.

Anti-solar phenomena (anti-coronae, shadow obscuration, rainbows, and sub-suns) have the limitation that for inner planets and small sun-planet-earth angles the scattering of the earth's atmosphere would mask any expected effect. This could be circumvented by use of satellite observations. They have the further limitation that for outer planets the accessible phase angle is small. (Mars barely qualifies for the primary water rainbow, for example.)



The unexplained variation in brightness of the Jovian planets may perhaps be accountable on the basis of planetary meteorological optics. Correlation with solar activity has not been satisfactory. Correlation with phase is unconfirmed. Until this receives a satisfactory explanation it would appear useless to attempt the subject studies for these planets.

Diffraction phenomena have the limitation that for outer planets a rather marginal effect would be further diminished (in frequency of occurrence and in intensity) by necessity for reflection as well.

SUMMARY

Mercury: The maximum angle that this planet makes with the sun is about 22°. Simple halo, aureole, and corona phenomena might therefore be observed, as well as rainbows and cloudbows, if storms covered a significant fraction of the sunlit side of the planet. While it is considered most unlikely that Mercury has sufficient atmosphere to support condensation phenomena or to give rise to dust storms, the possibility of dust clouds or haze resulting from solar radiation merits further consideration.

Unresolved surface features should yield measurable brightness differences in the neighborhood of opposition. Brightness observations at such small angles from the sun would need to be made outside the realm of scattering of sunlight by the Earth's atmosphere, that is, from Earth satellites, rockets, etc.

Venus: This planet can appear as much as 43° from the sun, probably has a complete condensation system, and is near enough to permit observation of relatively small brightness differences. Knowledge of the angular position and dispersion of rain- and cloud-bow phenomena could establish the chemical composition of the cloud material, and give information concerning particle size distribution. Venus is well-suited for such terrestrial based studies.

Shadow observation near opposition and corona studies near inferior conjunction would give information concerning cloud structure and meteorology: Failure to observe an increase in brightness due to shadow obscuration would mean that upper cloud layers were rather smooth or smoothly graded. Either of these situations would constitute circumstantial evidence against violent meteorological activity. The extent and nature of brightness increase would be determined by texture, thickness of uppermost layers, and extent of layering. If the upper clouds of Venus are smoothly graded, then corona phenomena should be quite generally observable which would give data on particle size.

If the planet is spin-stabilized, with axis tilted from the ecliptic, it is possible that meteorological ices occur in polar regions, and that simple halo phenomena might be observed terrestrially. These would show an eight-month periodicity in intensity (or frequency) with amplitude of variation roughly proportional to tilt.

Among the rainbow, halo, corona, and shadow phenomena of Venus which might be detected from the Earth or just beyond its scattering atmosphere, it seems unlikely that all would be of sufficiently uniform areal distribution that nothing could be deduced concerning the rate of movement of the cloud cover, hence inferred of the length of the Cytherean day.

<u>Earth</u>: Anti-coronae are rare natural occurrences on the ground, but are more frequent in aerial observations. They are indicative of freshly formed droplets, whose size -- hence age -- can be determined from the angular radii of the colored rings. Possible significance of the age of a cloud from the point of view of weather prediction need not be emphasized. In addition to correlations of anti-coronae data with weather patterns in weather reconnaissance flights, the possibility of acquisition of such data from satellites would seem to be of interest.

Brightness differences at the anti-solar point in clouds are indicative of the local state of the atmosphere. This phenomenon might have practical value also.

Halos can be observed in aerial observations. The extent and nature of development of the phenomena in clouds are governed by temperature, wind velocity, and turbulence. Halos on snow surfaces would be a source of meteorological data from satellites in the absence of clouds. Again, it is not unreasonable to suppose a practical use for such data.

<u>Mars</u>: If there should be extensive rainstorms on Mars, it should be possible to observe from Earth the violet end of the primary rainbow. The red edge of the primary bow lies on a cone of half-angle $41^{\circ}20'$ coaxial with the source. The maximum half-angle cone with apex at Mars which could be intercepted by the Earth's orbit is $40^{\circ}58'$. This means that attainable data through both atmospheres would be restricted to the violet and near ultra-violet portions of the spectrum, for water rainbows, although cloudbows should be detectable.

The low surface temperature of Mars, along with accepted ideas concerning its atmospheric content and behavior, suggests that more could be learned about its atmosphere and meteorology from halo phenomena associated with floating ice crystals or surface hoar frost on the planet. The 22° halo phenomena ought to be readily observable.

The anti-solar shadow phenomenon is of interest also; on the assumption that gross unresolved surface features are due to terrain, the extent of erosion which has resulted from atmospheric processes might be estimated.

Anti-coronae are likely to be more prevalent than on Earth; if these should be observed, estimates of composition could be made, based on dispersion.

Further thought should be given to the possibility of detecting dust storms on the red planet, by means of reflected diffraction phenomena.

<u>Major Planets</u>: Jupiter, Saturn, Uranus, and Neptune are sufficiently cold in surface temperature that analogs of terrestrial halo phenomena (resulting from meteorological ices) might be studied in detail. Ammonia and methane crystals of special shapes and with characteristic refractive index, hence characteristic angles of minimum deviation, should result in definitive characteristic angles of maximum reflection to Earth after refraction in individual crystals. Some of these angles might be accessible along the Earth's orbit.

These planets are so far away that rainbow phenomena could not be observed more easily than to send a probe directly. But anti-coronae could be observed. Mie scattering theory could be developed to determine whether a search for such phenomena on the major planets would be worthwhile.

Existence and character of extensive planetary aerosols might be established (analogs of snowstorms, dust storms, or clouds) by observation of diffraction phenomena at times near opposition.

Antisolar shadow studies might provide some idea of surface features. In the past, this idea has been applied to determination of the granular nature of Saturn's rings.

Observations of brightness variations with phase for the major planets have not been accounted for, and the data appear to be in conflict. If these are not, in fact, manifestations of meteorological phenomena analogous to terrestrial phenomena, then this would all but preclude observations of the type considered.

At the present time, the promising avenues would seem to be limited to a search for

1) shadow obscuration on Mercury, observed from satellites.
2) anti-coronae, rainbows, halos, and coronae on Venus.
3) applications of the subject phenomena to Earthian weather forecasting.
4) anti-coronae, shadows, rainbows, and halos on Mars.
5) anti-coronae, shadows, and halos on Jupiter.
6) shadows on Saturn and its rings.

REFERENCES

AIRY, G. B., (full explanation of the rainbow) Camb. Phil. Trans. 6, 379 (1838).

ALBRECHT, F., (back-scattered light in deep clouds) Meteorol. Zpravy 50, 478-86 (1933).

ALBY, E., Optical phenomena in supercooled stratus seeded with silver iodide, Puy de Dôme Obs., Bull. Ser. 2, 2, 51 (1953).

ÅNGSTROM, A., The blue sun of September, 1950, Tellus 3, 135 (1951).

ARCHENHOLD, G., (27 day period of halo frequency) Beitrage zur Geophys. 39, 141 (1933).

ARCHENHOLD, G., (elaborate memoir) ibid., 53, 395 (1938).

ASHBROOK, J. (Period of brightness variation for Uranus) Pub. Astron. Soc. Pac. 60, 116 (1948).

ASHBURN, E. V., AND R. G. WELDON (NOTS) Spectral diffuse reflectance of desert surfaces, JOSA 46, 583 (1956).

BECKER, W. (Fluctuations in reflectivity of major planets) Sitzb. Preuss. Akad. Wiss. Phys. Math. Kl. 28, 839 (1933); Astr. Nach. 277, 65 (1948).

BALASTER, G. A., Theory of rainbow and corona phenomena from the electromagnetic point of view. Ph.D. Thesis, Zurich, 1951.

BARATOUX, M., Optical phenomenon observed from an airplane. La Meteorologie, Ser. 4, No. 34, 171-172, 1954. (MH-BH)/Blue Hill Obs.

BENNETT, H. E. and J. M., and M. R. NAGEL, Question of polarization of infra-red radiation from the clear sky, JOSA 51, 237 (1961).

BLACK, D. M., The brocken spectre of the desert view watch tower, Grand Canyon, Arizona. Science 119, 164 (1954).

BLACKADAR, A. K., see Lowell Observatory.

BOBROV, M. S. Derivation of the theoretical phase function of the brightness of Saturn's rings and its comparison with observations. Astron. Zh. 36 (1), 129 (1959) Sov. Astron. AJ 3 (1) 131 (1959); 3 (5), 839 (1960); 4 (2), 288 (1960) .

BOYER, C. B., The rainbow; from myth to mathematics. (T. Yoseloff, N. Y., 1959).

BULL, G. A., Blue sun and moon. Meteorology Mag. 80, 1 (1951).

BOBROV, M.S. Some remarks on optical properties of Saturn's rings. Astron. J. 65, 337 (1960).

CHAZY, J., Blue sun, L'Astronomie 65, 68 (1951).

CHANDRASEKHAR, S. Radiative Transfer (Clarendon, Oxford, 1950) Ch. V, VI.

CHRISTIE, A. W., The luminous directional reflectance of snow, JOSA 43, 621L (1953).

COLEMAN, H. S., and H. E. ROSENBERGER (U. Texas) The effect of wavelength on the attenuation of brightness contrast by the atmosphere. JOSA 40, 263A (1950).

COX, C., and W. MUNK (SIO) Measurement of roughness of the sea surface from photographs of the sun's glitter. JOSA 44, 838 (1954).

CURCIO, J. A., Evaluation of atmospheric aerosol particle size distribution from scattering measurements in the visible and infra-red. JOSA 50, 548 (1960).

DEIRMENDJIAN, D., and Z. SEKERA (UCLA) Quantitative evaluation of multiply scattered and diffusely reflected light in the direction of a stellar (sun) source in a Rayleigh atmosphere. JOSA 43, 1158 (1953).

DEIRMENDJIAN, D., Theory of the solar aureole, Pt. 1. Rand Res. Memo RM2008, 10/57.

DEIRMENDJIAN, D., Theory of the solar aureole, Pt. 2. Rand Res. Memo RM2133, 2/58.

DEIRMENDJIAN, D., Atmospheric scattering of light and the sun's aureole.

DEIRMENDJIAN, D., Theory of the solar aureole. Ann. de Géophys. (Paris) 13, 286 (1957).

DEIRMENDJIAN, D., Note on the Photometry of the sea surface. JOSA 52, 1083 (1962).

DESCARTES Meteors (Leyden, 1637).

DESSEUS, H., The blue sun of 1950 September. LaMeteorologie No. 22, 128 (1951).

DE VORE, J. R., and A. H. PFUND. Optical scattering by dielectric powders of uniform particle size. JOSA 37, 826 (1947).

DIETZIUS, R., (reflectance from ground) Beitr. Phys. freien Atm. 11, 69-74 (1923)

DLUZHNEVSKAIA, O. B. Contrasts between maria and continents and between edge and cap on Mars in 1956 and 1958. Vses. Astro-Geodez. Obsh. #27 (34), 10 (1960).

DOLLFUS, A. Study of the planets by the polarization of their light. Ann. d'Astrophys. Supp. 4 (1957).

DOLLFUS, A. Polarimetric study of the light reflected by clouds and atmosphere of the planet Mars. Compte rendu 227, 383 (1948).

DONCASTER, L. (Glorification of B. Cellini) Nature 90, 621 (1913).

DOUGLAS (Coronae and anti-coronae from aircraft) Met. Mag. 56, 67 (1921).

DURST, C. S., and G. A. BULL An unusual refractive phenomenon seen from a high-flying aircraft Met. Mag. 85, 237 (1956).

DUNTLEY, S. Q. Reduction of apparent contrast by the atmosphere JOSA 38, 179 (1948).

DUNTLEY, S. Q. The reflection of light by water waves, JOSA 41, 287A27 (1951).

DUNTLEY, S. Q., J. H. HOOD, R. W. AUSTIN, and A. R. BOILEAU Aerial measurements of some optical properties of the atmosphere. JOSA 45, 905A51 (1955).

ELDRIDGE, R. G., and J. C. JOHNSON Distribution of irradiance in fog and haze JOSA 52, 787 (1962).

FIRSTOFF, V. A. Dissipation of planetary atmospheres. Science 130, 1337 (1959).

FLAMMARION, C. (Anti-coronae at shadow of balloon) L'Atmosphere p. 232 (1888).

FULKE, WM. Goodly Gallery with a Most Pleasaunt Prospect into the Garden of Naturall Contemplation, to Beholde the Naturall Causes of All Kind of Meteors. (W. Griffith, London, 1571).

GALLE, J. G., and A. BRAVAIS (Classic treatment of halos) J.l'Ecole roy.polytech. (1847).

GÄBLER, H. Rare halo appearance near the ground. Z. Meteor. 8, 127 (1954).

GIBBONS, M. G., J. R. NICHOLS, F. I. LAUGHRIDGE, and R. L. RUDKIN. Transmission and scattering properties of a Nevada desert atmosphere JOSA 51, 633 (1961).

GIBBONS, LAUGHRIDGE, NICHOLS, and N. A. KRAUSE Transmission and scattering properties of a Nevada desert atmosphere under cloudy conditions JOSA 52, 38 (1962).

GEHRELS, T. Wavelength dependence of the polarization of the sunlit sky JOSA 52, 1164 (1962).

GICLAS, H. L. See Lowell Observatory.

GORDON, S. A green sun after sunset. Meteor. Mag. 87, 277 (1958).

GUERIN, P. New research on Mars. Nature (Paris) 1959, 526.

GUSEV, I. I. Observations of the rotation of Venus. Vsesoiuzhoe Astro-Geodez. Obsh., #23 (30), 51 (1958).

HAUPT, H. Observations and the relative photometry of a halo. Wetter und Leben, Wien 9, 19 (1957).

HENINGER, S. K. A handbook of renaissance meteorology (Duke Univ., 1960).

HESS, S. L. See Lowell Observatory.

HESS. S. L. Blue haze and the vertical structure of the Martian atmosphere. Astrophys. J. 127, 743 (1958).

HILL, T. Contemplation of mysteries (H. Denham, London, 1571).

HO., P., and J. NEEDHAM Ancient Chinese observations of solar haloes and parhelia Weather, London, 14(4), 124(1959).

HOLMES, F. M. E., and B. O'BRIEN Transmission of light by fog and haze JOSA 22, 9A (1932).

HORAK, H. G. Diffuse reflection by planetary atmospheres. Astrophys. J. 112, 445 (1950).

HOUGHTON, H. G., and W. R. CHALKER (MIT) The scattering cross-section of water drops in air for visible light. JOSA 39, 955 (1949).

HOUSTOUN, (Geometrical treatment of rainbows due to Descartes) (Longmans, 1930) p. 112.

HERZBERG, G. Spectroscopic evidence of molecular hydrogen in the atmospheres of Uranus and Neptune. Astrophys. J. 115, 337 (1952).

HULBURT, E. O. The ultra-violet, visible, and infra-red reflectivities of snow, sand, and other substances. JOSA 17, 23 (1928).

HULBURT, E. O. Optics of atmospheric haze. JOSA 31, 467 (1941).

HUMPHREYS, W. J. Some unusual halos. JOSA 7, 62A (1923).

HUMPHREYS, W. J. Physics of the air. (McGraw-Hill, N. Y., 1940).

ISAACS, J. D., and J. E. TYLER On the observation of unresolved surface features of a planet. Pub. Astron. Soc. Pacific, 72, No. 426, 159 (1960).

ISRARDI, T. Investigation of turbid media. Ann.d. Phys. 62, 573 (1920).

IVES, R. L. Sunset shadow bands. JOSA 35, 736 (1945).

JACQUINOT, P., and C. SQUIRE Note on reflection and diffraction from ice crystals in the sky. JOSA 43, 318L (1953).

JEANS, J. The physical condition of the planets. Nature 147, 526 (1941).

JENNE, W. The phenomenon "blue sun" Tellus 3 (3) 129-134 (Aug., 1951).

JOHNSON, E. A., R. C. MEYER, R. E. HOPKINS, and W. H. MOCK (DTM). The measurement of light scattered by the upper atmosphere from a searchlight beam. JOSA 29, 512 (1939).

JOHNSON, H. See Lowell Observatory.

KERKER, M., and M. I. HAMPTON The use of unfiltered light in determining particle radius by the polarization ratio of the scattered light JOSA 43, 370 (1953).

KHAN, M. A. R. Early theory of rainbows. Weather 10, 358 (1955).

KLINOV, F. I. Halo and ice crystals. Priroda 44, 85 (1955).

KOHLER, H. (Abnormal corona observed in mist) Meteor. Zs. 46, 164 (1929).

KOVAL, I. K. Results of photographic observations of Mars at the Kharkov Astronomical observatory during 1954 Astron. Zh. 34, 412 (1957). [Sov. Astron. AJ 1 (3), 404 (1957)] .

KOVAL, I. K. Degree of smoothness of continents and maria on Mars. Akad. Nauk SSSR Kom. Fiz. Planet, #1, 85 (1959).

KRAUL, W. Blue color of the sun in September, 1950. Z. Meteor. 6, 253 (1952).

KRAUS, J. D. Rotation period of the planet Venus as determined by radio observation. Nature 178, 687 (1956).

KRYLOV, P. A. Solar halos observed at high altitudes. Akad. Nauk SSSR, Ser. Geofiz. 2, 81-84 (1952).

KUIPER, G. P. Planetary and satellite atmospheres. Repts. Prog. Phys. 13, 247 (1950).

KUIPER, G. P. The atmospheres of the earth and planets. (Univ. Chicago, 1952)

KUIPER, G. P. Determination of the pole of rotation of Venus Astrophys. J. 120, 603 (1954a)

KUIPER, G. P. The earth as a planet. (Univ. Chicago, 1954b).

KUIPER, G. P. Planets and satellites. (G. K. and B. M. Middlehurst, Eds.) (Univ. Chicago, 1961).

KUIMOV, K. V. Venus in 1954. Vses. Astro-Geodez. Obsh. #21 (28), 30 (1958).

KULINOVSKII, P. N. Observation of a rainbow from an airplane. Priroda, #11, 1958.

KUPETSKIĬ, V. N. Observation of a rainbow from an airplane. Priroda, 7, 127 (1959).

KUSIN, G. E. Photograph of a halo. Priroda 46, 116 (1957).

LACY, R. E., M. A. ELLISON, and S. E. ASHMORE. The halo display of March 2, 1954, Weather 9, 206 (1954).

LANDER, R. L., and C. E. NIELSEN Scattering of light from small drops Rev. Sci. Inst. 24, 20 (1953).

LILJEQUIST, G. H., Halo phenomena and ice crystals. Norwegian, British, Swedish Antarctic Expedition 1949-1952, Scientific Results. Vol. 2, Pt. 2A (Norsk Polarinst., Oslo, 1956).

LINK, F. Transits of Venus across the sun. Bull. Astron. Insts. Czech. 10, 105 (1959).

LINK, F. Lengthening of the cusps of Venus. Soc. Roy. Sci. Liège. Mem. Ser. 4, 18, 148 (1957).

LOEWE, F. Discussion of 8 years of aerological observations obtained by means of aeroplanes near Melbourne. Austral. Met. Br., Bull. 27 (1940).

LOEWE, F. (6 years, near Sydney) ibid., Bull. 33 (1945).

LOEWE, F. (4 years, near Perth) ibid., Bull. 37, (1946).

LORENZ, E. N. See Lowell Observatory.

LOWELL OBSERVATORY Project on Planetary Atmospheres. Flagstaff, Arizona. CWB-7896, Report No. 1, 1/1/48 to 7/1/48 (Hess and Panofsky). Report No. 2, 7/1/48 to 1/1/49 (Hess and Johnson). Report No. 3, 1/1/49 to 6/30/49 (Hess, Panofsky, and Giclas) AF-19 (122)-162, Report No. 1, 8/1/49 to 10/31/49 (Blackadar) Mars. Report No. 2, 11/49 to 2/50 (Blackadar) Jupiter, Mars Report No. 3, 2/50 to 5/50 (Blackadar) Jupiter. Report No. 4, 5/50 to 8/50 (Blackadar) Saturn. Report No. 5, 8/49 to 10/50 Bibliography, 1920-1950. Report No. 6, 9/50 to 1/51 (Shapiro) Mars. Report No. 7, 1/51 to 4/51 (Shapiro) Earth, Jupiter. Report No. 8, 4/51 to 7/51 (Shapiro) Earth, Jupiter. Report No. 9, 6/30/51 to 9/30/51 (Final), (Lorenz) Jupiter.

MAIER, W. Ice crystal haloes. Z. Meteor. 4, 111 (1950).

MALKUS, W. V. R. Rainbows and cloudbows. Weather 10, 331 (1955).

MARQUARDT, W. An unusual halo phenomenon near the ground Z. Meteor. 13, 133 (1959).

MECKE, R. The scattering and diffraction of light by mist and clouds Ann. der Phys. 65, 257 (1921).

MENZEL, D. H., and F. L. WHIPPLE The case for water clouds on Venus. Astron. Soc. Pac. 67, 161 (1955).

MEYER, R. Double shadows Z. Meteor. 4, 1,245 (1950).

MEYER, R. Optics of drops. Pt. 2. Coronas, glories, etc. Handbuch der Geophysik, Berlin, Vol. 8, Lief. 5, 898 to Lief. 6, 942 (1956).

MEYER, R. Rainbows, halos, shadows, etc., illustrated. Linkes Meteorologische Taschenbuch (Leipzig, 1957).

MIDDLETON, W. E. K. Visibility in meteorology (Univ. Toronto, 2nd Ed., 1941).

MIDDLETON, W. E. K. The "diffusing effect" of fog. JOSA 32, 139 (1942).

MIDDLETON, W. E. K. The colors of distant objects. JOSA 40, 373 (883) (1950).

MIDDLETON, and H. G. MUNCALL The luminous directional reflectance of snow JOSA 42, 572 (1952).

MIDDLETON, W. E. K. The color of the overcast sky. JOSA 44, 793 (1954).

MIDDLETON, W. E. K. Random reflections on the history of atmospheric optics JOSA 50, 97 (1960).

MIERDEL, F. Study of artificial Brocken bows. Beit. Physik freien Atmosphäre 8, 95 (1919).

MIKIROV, A. E. Assymmetry of diffusion index of a transparent sphere Akad. Nauk SSSR 10, 1258 (1958).

MILI, G. Visibility of signals through fog. JOSA 25, 237 (1935).

MINNAERT, M. The reflection of light in rippled surfaces. Physica 9, 925 (1942).

MINNAERT, M. The nature of light and colour in the open air. (Dover, N. Y., 1954).

MOON, P. (Radiation incident on a cloud) J. Franklin Inst. 230, 583 (1940).

MOON, and D. E. SPENCER, (Theory of overcast sky brightness) Illum, Eng. 37, 707 (1942).

McCONNEL, The theory of fog-bows. Phil. Mag. 29, 456 (1890).

NAGEL, M. R. On the spectral distribution of energy in outdoor scenes under the influence of light reflected from neutral gray ground JOSA 41, 292A60 (1951).

NAIK, Y. G. (Corona formation, based on Mie theory) J. Colloid Sci. 9, 393 (1954).

NAIK, Y. G. and R. M. JOSHI Anti-Coronas or Brocken Bows. JOSA 45, 733 (1955).

NEUBERGER, H. On the relation between solar activity and halo phenomena Beitrage zur Geophys. 51, 343 (1937).

NEWKIRK, G. A. Photometry of the solar aureole JOSA 46, 1028 (1956).

NEWTON, I. Opticks (Book i, Pt. 2, Prop. 9) (1704).

NRC COMMITTEE ON ATMOSPHERIC SCIENCES The Atm. Sciences 1961-1971 NAS-NRS Pub. 946 (1962).

PACKER, D. M., and C. LOCK The brightness and polarization of the daylight sky at altitudes of 18,000 -- 38,000 feet above sea level JOSA 41, 473 (1951).

PANOFSKY, H. A. See Lowell Observatory.

PERNTER-EXNER Meteorologische Optik (W. Braumüller, Wien, 1910)

PENNDORF, R. "Blue sun" again Umschau 52, 320 (1952).

PONCELET, L. A curious phenomenon of atmospheric refraction. Ciel et Terre 71, 350 (1955).

POWELL, W. M., and G. L. CLARKE The reflection and absorption of daylight at the surface of the ocean. JOSA 26, 111 (1936).

RAY, B. B. The scattering of liquid droplets, and the theory of coronas, glories and iridescent clouds. Proc. Ind. Assoc. for the Cultiv. of Sci. 8, 23-46 (1923).

RENAUD, A. (22° and 46° halos on level snow surface) Compte rendu 206,1750 (1938).

RICHARDS, P. I. Scattering from a point source in plane clouds JOSA 46, 927 (1956).

RICHARDSON, R. S. Spectroscopic observations of Venus for rotation made at Mt. Wilson in 1956. Astron. Soc. Pac. 70, 251 (1958).

RODEWALD, M. The blue sun of 9/27/50 Naturw. Rundschau 5, 8 (1952).

RUBASHEW, B. M. New findings regarding physical conditions on Venus. Priroda 39, 37 (1950).

SANSON, J. Localities where blue suns and blue moons were noticed 9/27/50 La Meteorologie Ser. 5, 22, 132 (1951).

SCHIELDRUP-PAULSEN, H. "Blue" sun Naturen (Bergen) 76, 336 (52).

SCHOENBERG, E. and LEBEDINETS (Brightness of Saturn's rings) Cf. Handbuch Astrophysik 2 (1), 4, 148 (1929).

SCHRODER, W. Observation on the Rönnebeck halo phenomenon Met. Rundschau 13, 14 (1960).

SCHUSTER, A. (Diffuse radiation in stellar atmospheres) Astrophys. J. 21, 1-22 (1905).

SHAPIRO, R. See Lowell Observatory.

SHARANOV, V. V. Photometric investigation of the nature of planets and satellites. Uspekhi Astron Nauk 6, 181 (1954).

SHARANOV, V. V. Existence of a correlation between color and phase for Mars. Astronom. Tsirk. (Moscow) 208, 11 (1960).

SHIFRIN, K. S. and I. I. Rabinowich Spectral indices of large water drops and the spectral polarization of rainbows. Akad. Nauk SSSR 12, 1491 (1957).

SIMPSON (Iridescent clouds as fragments of coronas). Quart. J. Roy. Met. Soc. 38, 291 (1912).

SINCLAIR, D. Light scattering by spherical particles. JOSA 37, 475 (1947).

SINGLETON, F., M. J. KERLEY, and D. J. SMITH Recent observations from aircraft of some rare halo phenomena. Weather 15, 98 (1960).

SMITH, A. G. Daylight visibility of stars from a long shaft. JOSA 45, 482 (1955).

SQUIRE, C. F. Note on reflection and diffraction from ice crystals in the sky. JOSA 42, 782L (1952).

STAMM, G. L., and R. A. LANGEL JOSA 51, 1090 (1961).

STAMM and LANGEL Some spectral irradiance measurement of upwelling natural light off the east coast of the United States.

STENG. E. Blue sun. Gaz. obs. PIHM Warsaw 4(1), 2-3 (1951).

STEBBINS, J., and T. S. JACOBSON (Fluctuation of brightness of Uranus) Bull. Lick Obs. 13, 180 (1928).

THEISSING, H. H. Macrodistribution of light scattered by dispersions of spherical dielectric particles. JOSA 40, 232 (1950).

TYNDALL, J. Note on the white rainbow. Phil. Mag. 17, 148, 244 (1883).

TOOLIN, R. B., and STAKUTIS, V. J. Qualitative indication of nadir sky blue. JOSA 48, 71 (1958).

UREY, H. C. The planets; their origin and development. (Yale Univ. Press, 1952).

UREY, H. C. The atmospheres of the planets. Handbuch der Physik 52, 363 (1959).

UREY, H. C. (Comment on blue haze on Mars) Astrophys. J. 128, 736 (1958).

VAN DE HULST, H. C. Optics of spherical particles (Utrecht, 1946).

VAN DE HULST, H. C. A theory of the anti-coronae JOSA 37, 16 (1947).

VAN WIERINGEN, J. S. (Light reflection from water surfaces). Proc. Koninkl. Ned. Akad. Witenschap. 50, 952 (1947).

VARLEY, B. C. Seeing is believing. Weather 10, 355 (1955).

VERDET, C. R. (Theory of coronas) Ann. chim. et phys. 34, 137 (1852).

VISSER, S. W., and CTJ ALKEMANDE A tangent arc of the halo of 24-1/2 degrees. Roy Met. Soc., Quart. J., 82, 92 (1956).

VISSER, S. W. Optical phenomena in the sky. Meteor. Inst. Ned. #3 (1957).

VISSER, S. W., An unknown phenomenon, the outer rim of the 22° halo. Hamel en Dampkring 55, 228 (1957).

VISSER, S. W., Halos without a small ring. Hemel en Dampkring (Hague) 57, 260 (1959).

VON LOMMEL (heiligenschein) Ann. d.Phys. 1874 Jubelband 10.

VOLZ, F. Color photography in atmospheric optics. Pt. 3. Cloud halos, coronas, and rainbows. Photographie und Wissenschaft. (Agfa) 4, (1955) (6pp. with color photos). Optics of drops. Lief. 6 of Vol. 8 of Handbuch der Geophysik. Berlin, 1956.

VISSER, S. W. Halo phenomena ibid.

VOLZ, F. E. Some aspects of the optics of the rainbow and the physics of rain. Am. Geophys. Union, Geophys. Monogr. 5, 280-286 (1960).

WHIPPLE, F. L. Earth, moon and planets. (Grosset and Dunlap, N. Y., 1958).

WHITNEY, A. W. (22° and 46° halos on level snow surface). Am. J. Sci. 45, 389 (1893).

WIENER, C. (angular distribution of radiation reflected and refracted by a spherical drop) Nova Acta Leopoldina 73, iii-xii, 3-239 (1907); 91, iii-vii, 81-292 (1910).

WILSON R. The blue sun of 1950 September Roy. Astron. Soc., Monthly Notices 3, 478-489 (1951).

WILTBERGER, P. B. (Color and aviation) J. Aviat. Med. 10, 47-49 (1939).

WOOD, R. W. Physical optics (MacMillan Co., N. Y., 1936).

WOOLARD, E. W. (Geometrical theory of halos) Monthly Weather Review 69, 260-262 (1941).

CHASE, S. D., L. D. KAPLAN, and G. NEUGEBAUER, (Infra-red radiometry, Mariner II) Science 139, 907 (1963).

FRANK, L. A., J. A. VAN ALLEN, and H. K. HILLS, Charged particle measurements in the vicinity of Venus with the SUI experiment on Mariner II. Science 139, 905 (1963).

GOLDSTEIN, R. M., and R. L. CARPENTER (Doppler measurement of rotation period of Venus) Science 139, 909 (1963).

LILLEY, A. E., and A. H. BARRETT, Mariner II microwave observations of Venus. Science 139, 906 (1963).

SMITH, E. J., L. DAVIS, P. J. COLEMAN and C. P. SONETT (Magnetometer, Mariner II) Science 139, 908 (1963).

TAYLOR, J. H., Daytime visibility of stars by the high altitude observer NObs-72039, Task 5, Reports 5-8 and 5-9, June, 1960.