Circular Polarization of Sunlight Reflected by Clouds

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ABSTRACT

Measurements of circular polarization of visible light from planets have recently been reported. It is pointed out here that the values measured for the circular polarization for Jupiter and Venus are of the magnitude expected for sunlight reflected by a cloudy planetary atmosphere. The variations of the sense of the polarization with phase angle and with location on the planetary disk are also consistent with expectations for reflection by clouds.

Kemp *et al.* (1971a, b) have recently reported measurements of "circular" polarization of light from planets. They measure the ratio of Stokes parameters V/I and have obtained values $\sim 10^{-4}$ with the sign of V generally opposite in the Northern and Southern Hemispheres of each planet. Where sufficient measurements exist, they also find that the sign of V reverses when the planet passes through zero phase angle. It is worth pointing out that all of these characteristics conform to our expectations for sunlight reflected by a cloudy planetary atmosphere, and, in particular, that the magnitude of V/I is similar to values we obtained in calculations for model terrestrial clouds [Hansen (1971a, b); these papers are referred to here as I and II, respectively].

The calculations reported in II were for a phase matrix of the type [see (23) in I and (5) in II]

$$\mathbf{P}(\mu,\mu_0,\phi-\phi_0)=\begin{bmatrix} \mathbf{c} & \mathbf{c} & \mathbf{s} & 0 \\ \mathbf{c} & \mathbf{c} & \mathbf{s} & \mathbf{s} \\ \mathbf{s} & \mathbf{s} & \mathbf{c} & \mathbf{c} \\ 0 & \mathbf{s} & \mathbf{c} & \mathbf{c} \end{bmatrix}, \qquad (1)$$

where **c** represents even matrix elements (which contain only cosine terms in a Fourier expansion in the azimuth angle $\phi-\phi_0$; see I), **s** represents odd matrix elements (containing only sine terms), and 0 represents matrix elements which are identically zero. The form of the phase matrix (1) is valid for randomly oriented, nonspherical particles which have a plane of symmetry, as well as for spherical particles (van de Hulst, 1957; Hovenier, 1969). Thus, for this quite general type of phase matrix, the single scattering of incident unpolarized sunlight yields $V=0$.

The reflection (and transmission) matrices for multiple scattering may be obtained by taking products of matrices which are of the type of the phase matrix. Thus, when multiple scattering occurs, the reflection matrix has the form

$$\mathbf{R}(\mu,\mu_0,\phi-\phi_0)=\begin{bmatrix} \mathbf{c} & \mathbf{c} & \mathbf{s} & \mathbf{s} \\ \mathbf{c} & \mathbf{c} & \mathbf{s} & \mathbf{s} \\ \mathbf{s} & \mathbf{s} & \mathbf{c} & \mathbf{c} \\ \mathbf{s} & \mathbf{s} & \mathbf{c} & \mathbf{c} \end{bmatrix} \qquad (2)$$

for the assumed type of phase matrix. Thus, a nonzero value for the element in the fourth row, first column arises from multiple scattering. According to the comments in Section 5b of II, this element should be small in value. For water clouds we found[1] $|V|/I=|R^{41}|/R^{11}$ to be typically $10^{-5}-10^{-3}$, which is of the same order as the values measured for Venus and Jupiter by Kemp *et al.* (1971b).

The opposite signs for V/I in the two planetary hemispheres and the switch in signs as the planet passes through zero phase angle are easily understood from the form of the reflection matrix above. Two points located symmetrically about a planet's intensity equator have the same zenith angles (μ,μ_0) but their azimuth angles are $\phi-\phi_0$ and $-(\phi-\phi_0)$. Thus, if the physical conditions are the same at the two locations, V/I will have the same absolute value but the opposite sign, because it is an odd function of $\phi-\phi_0$. The most likely cause of deviations from such a symmetry for V/I would be large-scale asymmetries on the planet about the intensity equator, such as variations in the local planetary albedo or variations in the composition of the scattering material. However, a similar result could be obtained in other ways (e.g., if the scatterers were nonspherical and preferentially oriented).

The switch in sign of V/I as the phase angle $\beta(=\pi-\alpha)$ passes through zero can be explained similarly. If $(V/I)_\beta$ refers to the value of V/I at the phase angle β in one particular hemisphere at the point $(\mu,\mu_0,\phi-\phi_0)$, then at the phase angle $-\beta$ the mirror point in the same hemisphere (same μ,μ_0) has the azimuth angle $-(\phi-\phi_0)$. Thus, $(V/I)_\beta=-(V/I)_{-\beta}$ if the physical conditions are the same at the two points and if the reflection matrix is of the assumed type [Eq. (2)].

Two conclusions follow immediately from the magnitude of V/I computed for terrestrial clouds and the above comments. First, because several planets (including Jupiter and Venus) are known to be covered by cloudy atmospheres, it seems clear that the observed circular polarization for these planets arises from multiple scattering by cloud particles. Second, the information content in the circular polarization of sunlight reflected by clouds (with the above, quite general, type of phase matrix) suffers from the limitation that the circular polarization arises only through the process of multiple scattering. This is contrary to the case for the linear polarization, which arises primarily from single scattering; it is this aspect of the linear polarization which allows a clear signature of the cloud microstructure to be read from the sharp features characteristic of single scattering by cloud particles. The precision with which atmospheric parameters can be derived from the circular polarization of reflected sunlight may thus be less than that which can be obtained from the linear polarization (see, e.g., Coffeen, 1969; Hansen and Arking, 1971; Hansen and Hovenier, 1971).

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REFERENCES

Coffeen, D. L., 1969: Wavelength dependence of polarization. XVI. Atmosphere of Venus. *Astron. J.*, **74**, 446–460.

Hansen, J. E., 1971a: Multiple scattering of polarized light in planetary atmospheres. Part I. The doubling method. *J. Atmos. Sci.*, **28**, 120–125.

——, 1971b: Multiple scattering of polarized light in planetary atmospheres. Part II: Sunlight reflected by terrestrial water clouds. *J. Atmos. Sci.*, **28**, 1400–1426.

——, and A. Arking, 1971: Clouds of Venus: Evidence for their nature. *Science*, **171**, 669–672.

——, and J. W. Hovenier, 1971: The doubling method applied to multiple scattering of polarized light. *J. Quant. Spectry. Radiative Transfer*, **11**, 809–812.

Hovenier, J. W., 1969: Symmetry relationships for scattering of polarized light in a slab of randomly oriented particles. *J. Atmos. Sci.*, **26**, 488–499.

Kemp, J. C., J. B. Swedlund, R. E. Murphy and R. D. Wolstencroft, 1971a: Circularly polarized visible light from Jupiter. *Nature*, **231**, 169–170.

——, R. D. Wolstencroft and J. B. Swedland, 1971b: Circular polarization: Jupiter and other planets. *Nature*, **232**, 165–168.

van de Hulst, H. C., 1957: *Light Scattering by Small Particles.* New York, Wiley, 470 pp.

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[1] Graphs of the ellipticity will be presented in a separate paper.