Scattering and Absorption by Nonspherical Particles in Planetary Atmospheres

Robert A. West

Jet Propulsion Lab, Calif. Inst. Of Tech., 4800 Oak Grove Dr., Pasadena, CA 91109 USA
tel: 818-354-0479, fax: 818-393-4619, e-mail: Robert.a.west@jpl.nasa.gov

Abstract

The atmospheres of Mars, the giant planets, and Titan all support populations of nonspherical particles. Analyses of observations of these atmospheres therefore rely on an understanding of the optical properties of nonspherical particles. We can glean information on particle size and composition from the wavelength dependence of the optical depth and from the shape of the forward peak of the scattering phase function. Additional information comes from polarization measurements which have been especially fruitful for Titan's haze. The Mars atmosphere contains mineral dust particles with effective radii near 1.6 micro meters, and water ice particles with radii between about 1 and 4 micro meters. The uppermost tropospheric hazes in Jupiter and Saturn are composed of ice crystals of ammonia, water and possibly traces of ammonium hydrosulfide, Methane ice and hydrogen sulfide ice are present in the atmospheres of Uranus and Neptune. Size estimation for these hazes in the giant planets is difficult, and even the expected spectral signatures are elusive. Titan's haze is both forward scattering and strongly polarized – a combination which points toward a fractal aggregate structure of 10 – 100 or more organic monomers whose radius is about 0.06 micro meters. Polar stratospheric hazes on Jupiter and Saturn also display this characteristic.

1 Martian dust

Information on particle size can be gleaned from spectroscopy from the ultraviolet to the infrared, and from the size of the forward-scattering solar aureole observed by instruments on the ground. The aureole is insensitive to particle composition and provides a better estimate of particle effective radius. The most accurate assessment of particle size was done with data from the IMP instrument on the Mars Pathfinder. Table 1 from Tomasko et al. [1] summarizes the analysis of these data and previous results. Tomasko et al. [1] and studies by Pollack et al. [2] and by Clancy et al. [3] find effective radii near 1.6 μm.

Table 1. Summary of Measurements of Mean Cross-Section-Weighted Size and Variance of Martian Aerosols

Author	Parameter	$\langle r_{eff} \rangle$, μm	v_{eff}	Comment
Pollack et al. [1977]	a = 0.4, b = 0.15	0.4	0.15	superseded by Pollack et al. [1995] due to lack of vignetting correction
Toon et al. [1977]	alpha = 2, gamma = 0.5, r_m = 0.4	2.75	0.42	observations at 5–40 μm wavelength from Viking orbiter
Pollack et al. [1979]	same as Toon [1977]	2.5	0.4	superseded by Pollack et al. [1995] due to lack of vignetting correction
Drossart et al. [1991]	alpha = 1, gamma = 1, r_m = 0.31	1.24 (somewhat uncertain)	0.25	spectra from ~1 to 3 μm wavelength from outside the atmosphere from the Phobos mission
Korablev et al. [1993]	alpha = 2, gamma = 1	0.8 at 25 km, 1.6 at 15 km	0.2 ± 0.1	solar occultations at 1.9 and 3.7 μm wavelength from Phobos mission
Pollack et al. [1995]	lognormal	1.85 ± 0.3, 1.52 ± 0.3	0.5 ± 0.3	Viking lander result replaces Pollack et al. [1977, 1979] papers
Clancy et al. [1995]	alpha = 1, gamma = 0.3, r_m = 0.014	1.8	0.997 (given as 0.8)	includes observations from the ultraviolet to the thermal IR to constrain width of size distribution
This work	a = 1.6, b = 0.2–0.5	1.6 ± 0.15	0.2–0.5 or more	preliminary result from IMP observations; no data from ultraviolet or thermal IR included

More recent studies by Wolff and Clancy [4] and Clancy and Wolff [5] of the spectral dependence of the optical properties reveal changes in particle size as functions of space and time. Dust particle effective radii over much

of Mars are similar to results found by Tomasko et al. [1] but smaller particles with effective radii near 1 µm appear in the northern hemisphere for part of the seasonal cycle, while somewhat larger particles appear during dust storms. Clancy and Wolff [5] also found two distinct sizes for ice crystals depending on latitude and season. The most common ice particles have effective radii near 1-2 µm, but another population with radii near 3-4 µm appears in the northern subtropical aphelion cloud belt.

2 Jupiter, Saturn, Uranus and Neptune

The visible appearance of giant planets is dominated by scattering and absorption by clouds and haze particles. Two or three kinds of particles are evident in the images. Outside of the polar regions the planets have bright and dark bands which are tinted a yellow-brown color. Evidence from methane band images sensitive to cloud altitude and other spectroscopy data indicate that we are seeing an upper Tropospheric haze layer which extends into the lower stratosphere on Saturn. For Jupiter and Saturn the most likely candidate is frozen ammonia, which is white. For Uranus and Neptune methane forms the uppermost condensate layer, although the dominant thick cloud layer is probably hydrogen sulfide ice. Another material of unknown composition but mixed in with the ice is responsible for the color which is most prominent on Jupiter. Infrared light can penetrate to levels as deep as 5 - 7 bars in the Jovian atmosphere, and thermochemical equilibrium models predict condensation clouds of ammonium hydrosulfide and a water-ammonia ice cloud near 2 and 5 bars, respectively. The Galileo Probe descended into Jupiter's atmosphere and a nephelometer measured particle densities during the descent. Instruments began recording data at 0.46 bar. There was a signature of a tenuous particle layer near 1.34 bar and no evidence for a water cloud. The absence of a water cloud and the low signal levels at other altitudes is attributed to the unusual meteorological environment where the probe entered. The type of region is know as a jovian hot spot because it relatively clear, allowing deeper upwelling radiation in the 5- µm spectral window to escape and produce high brightness temperature. These regions are relatively clear because of the action of dry downwelling air forced by the equatorial waves or some other mechanism.

Measurements of the intensity of light scattered at a variety of phase angles show that the scattering phase function is characteristic of particles that are comparable to or larger than the wavelength of visible light. Beyond that not much can be said of the tropospheric particles. The linear polarization of these particles is very weak and negative. Figure 1 shows images taken by the Cassini ISS instrument with orthogonal polarizers.
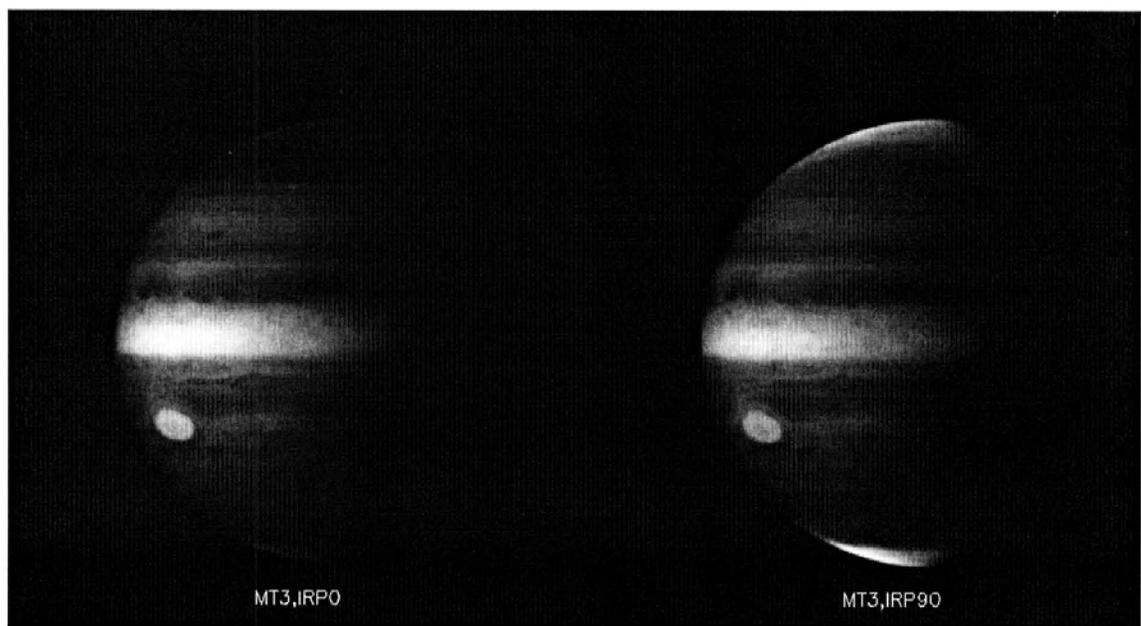

MT3,IRP0   MT3,IRP90

Figure 1

Comparison of the images in the two polarizers shows a polar haze that is strongly positively polarizing, and Tropospheric clouds which have very little polarization. Jupiter's Great Red Spot is a bright oval in these

methane-band images which are sensitive to cloud altitude. More will be said of the particles which produce the polar haze in the section below on Titan.

Spectral signatures of the expected icy constituents have been observed for Jupiter but not as commonly as expected. Ammonia ice should show absorption features at 3, 9.4 and 26 μm. The first two features have been observed but the third has not. Particle shape can influence the shape of some absorption features, and so West et al. [6] made one of the early applications of the discrete dipole array technique [7] in order to determine if nonspherical shape alone could account for non-detection of these features. Although features of ammonia and water ice have been observed it is still puzzling why they have not been observed more widely. A review of the aerosol and cloud observations for Jupiter was given by West et al. [8].

3. Titan and the polar stratospheres of Jupiter and Saturn

Titan's extended atmosphere contains an organic photochemical haze that is sufficiently optically thick to obscure the surface at visible wavelengths. Observations by the Pioneer and Voyager spacecraft showed that the upper part of the haze is both modestly forward scattering and very strongly polarizing. The polarization is similar to that from a Rayleigh-scattering atmosphere which would suggest very small particles. The forward-scattering phase function requires larger particles (about 0.3 μm effective radius). To reconcile these requirements West and Smith [9] proposed that aggregates of about 10 small (0.06 μm radius) monomers. This type of particle is expected as a result microphysical processes forming an organic haze. More recent models call for more monomers and a slightly larger monomer radius (see Rannou et al. [10]). A UV-absorbing haze in the atmospheres of Jupiter and Saturn displays similar optical properties and is also thought to be of an aggregate morphology, driven by organic chemistry in the auroral region.

4 Conclusion

Analyses of remotely sensed light scattered and emitted from the atmospheres of Mars, the giant planets and Titan have benefited from recent advances in understanding the optical properties of nonspherical particles. The Discrete Dipole code [7] and other codes for ellipsoids with a distribution of aspect ratio and codes for aggregates of spheres have been especially helpful. Yet there is still much we do not understand, such as particle size distribution in the giant planet ice clouds where the particles are probably angular in nature and beyond the size range suitable for dipole calculations. Improvements to these techniques and the development of entirely new techniques to handle these larger particles will be greatly welcomed.

Acknowledgement

References

[1] M. G. Tomasko, L. R. Doose, M. Lemmon, P. H. Smith, E. Wegryn "Properties of Dust in the Marian Atmosphere from the Imager on Mars Pathfinder," J. Geophys. Res. 104, 8987-9007 (1999).

[2] J. B. Pollack, M. E. Ockert-Bell, M.K. Shepard "Viking Lander Image Analysis of Martian Dust," J. Geophys. Res. 100, 5235-5250 (1995).

[3] R. T. Clancy, S. W. Lee, G. R. Gladstone, W. W. McMillan, T. Rousch "A New Model for Mars Atmospheric Dust Based upon Analysis of Ultraviolet through Infrared Observations from Mariner 9, Viking and Phobos," J. Geophys. Res. 100,5251-5263 (1995).

[4] M. J. Wolff and R. T. Clancy "Constraints on the Size of Martian Aerosols from Thermal Emission Spectrometer Observations," J. Geophys. Res. 108, No. 5097 (2003).

[5] R. T. Clancy, M. J. Wolff, P. R. Christensen "Mars Aerosol Studies with the MGS TES Emission Phase Function Observations: Optical Depths, Particle Sizes, and Ice Cloud Types Versus Latitude and Solar Longitude," J. Geophys. Res. 108 No. 5098 (2003).

[6] R. A. West, G. S. Orton, B. T. Draine, E. A. Hubbell "Infrared Absorption Features for Tetrahedral Ammonia Crystals," Icarus 80, 220-223 (1989).

[7] B. T. Draine and P. J. Flatau "Discrete-Dipole Approximation for Scattering Calculations," J. Opt. Soc. Amer. A 11, 1491-1499 (1994).

[8] R. A. West, K. H. Baines, A. J. Friedson, D. Banfield, B. Ragent, F. Taylor "Jovian Clouds and Haze" in Jupiter : The Planet, Satellites and Magnetosphere, F. Bagenal, T. E. Dowling, W. B. McKinnen, D. Jewitt, C. Murray, J. Bell, R. Lorenz, F. Nimmo Eds., (Cambridge Univ. Press, Cambridge, 2004)

[9] R. A. West and P. H. Smith "Evidence for Aggregate Particles in the Atmospheres of Titan and Jupiter," Icarus 90, 330-333 (1991)

[10] P. Rannou, M. Cabane, R. Botet, E. Chassefiere "A New Interpretation of Scattered Light Measurements at Titan's Limb"