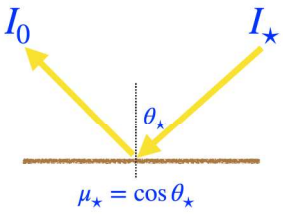
## The Reflection Law of Lambert:
## Lambertian Sphere

Equal brightness in all directions, regardless of viewing angle.

Johann Heinrich Lambert (1728-1777)

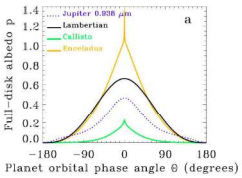



Lambert's cosine law:

$$I_0 = \mu_\star I_\star$$

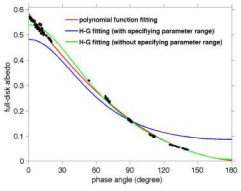
cosine of incident angle






Dyudina et al. (2016, ApJ, 822, 76)

## None of the Solar System bodies behave like Lambertian spheres!

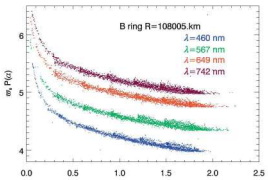



**Jupiter** (Cassini data)

Li et al. (2018, Nature Communications, 9, 3709)

See also: Mayorga et al. (2016)

**Notice the "cuspy" profiles!**





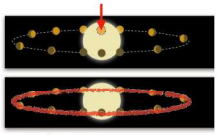
Deau et al. (2013, Icarus, 226, 591)



## Jargon

Since this is an old field of study, we will respect the established jargon.

| Quantity | Definition |
|---|---|
| Geometric albedo | Albedo at zero phase angle (superior conjunction) |
| Spherical albedo | Albedo over all phase angles |
| Bond albedo | Spherical albedo over all wavelengths |
| Phase integral | Ratio of spherical to geometric albedo |
| Single-scattering albedo | Fraction of light scattered in a single event |



$$A_B = \frac{\int A_s I_\star \, d\lambda}{\int I_\star \, d\lambda}$$

$$q = \frac{A_s}{A_g} = 2\int_0^\pi \Psi \sin\alpha \, d\alpha$$

$$\omega$$



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### The Albedo, Effective Temperature, and Energy Balance of Neptune, as Determined From Voyager Data

J. C. Pearl and B. J. Conrath

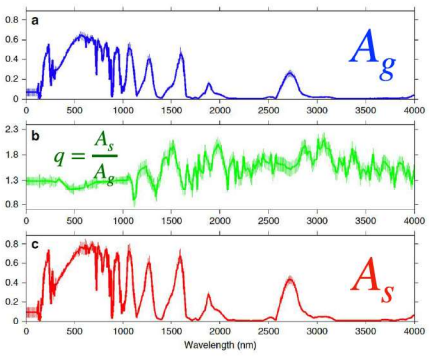
*NASA Goddard Space Flight Center, Greenbelt, Maryland*

TABLE 7. The Energy Balance of the Outer Planets, as Determined From Voyager IRIS Data

| Parameter | Jupiter[a] | Saturn[b] | Uranus[c] | Neptune[d] |
|---|---|---|---|---|
| Geometric albedo[e] | 0.274 ± 0.013 | 0.242 ± 0.012 | 0.215 ± 0.046 | 0.215 ± 0.050 |
| Phase intergral | 1.25 ± 0.1 | 1.42 ± 0.1 | 1.40 ± 0.14 | 1.35 ± 0.16 |
| Bond albedo[e] | 0.343 ± 0.032 | 0.342 ± 0.030 | 0.300 ± 0.049 | 0.290 ± 0.067 |
| Absorbed power,[e] $10^{16}$ W | 50.14 ± 2.48 | 11.14 ± 0.50 | 0.526 ± 0.037 | 0.204 ± 0.019 |
| Equilibrium temperature,[e] K | 109.5 ± 1.4 | 82.4 ± 0.9 | 58.2 ± 1.0 | 46.6 ± 1.1 |
| Emitted power, $10^{16}$ W | 83.65 ± 0.84 | 19.77 ± 0.32 | 0.560 ± 0.011 | 0.534 ± 0.029 |
| Effective temperature, K | 124.4 ± 0.3 | 95.0 ± 0.4 | 59.1 ± 0.3 | 59.3 ± 0.8 |
| Energy balance[e] | 1.67 ± 0.09 | 1.78 ± 0.09 | 1.06 ± 0.08 | 2.61 ± 0.28 |
| Internal power, $10^{16}$ W | 33.5 ± 2.6 | 8.63 ± 0.60 | 0.034 ± 0.038 | 0.330 ± 0.035 |
| Internal energy flux, $10^{-4}$ W/cm$^2$ | 5.44 ± 0.43 | 2.01 ± 0.14 | 0.042 ± 0.047 | 0.433 ± 0.046 |
| Internal power/unit mass, $10^{-11}$ W/kg | 17.6 ± 1.4 | 15.2 ± 1.1 | 0.392 ± 0.441 | 3.22 ± 0.34 |
| Luminosity: $\log(L/L_\odot)$ | −9.062 ± 0.034 | −9.651 ± 0.030 | $-12.054^{+0.327}_{\infty}$ | −11.025 ± 0.044 |



## The Cassini spacecraft has obtained exquisite data on reflected light from Jupiter



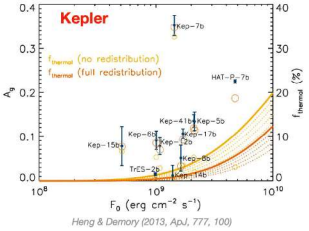

Li et al. (2018) substantially revised the Bond albedo of Jupiter:

$$A_B = 0.503 \pm 0.012$$

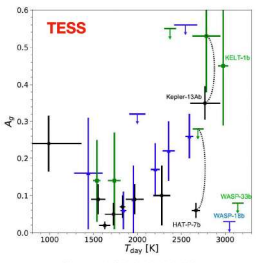
Li et al. (2018, Nature Communications, 9, 3709)



## The albedos of exoplanets (hot Jupiters)




Heng & Demory (2013, ApJ, 777, 100)




Wong et al. (2021, AJ, 162, 127)

Most hot Jupiters are **dark (geometric albedo ~0.1)**

Secondary eclipse depths of transiting exoplanets yield a mixture of reflected light and thermal emission (difficult to correct!)

To date, no strong trends with exoplanet or stellar properties