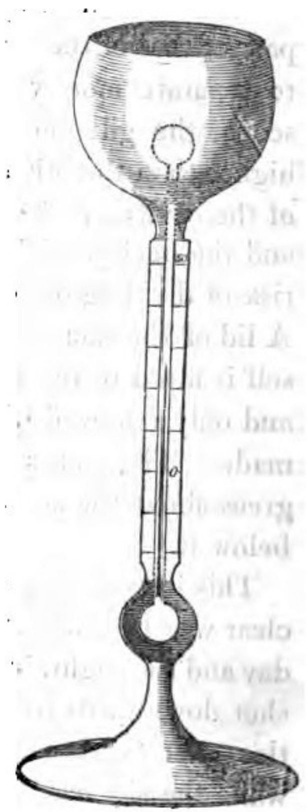
Radiation Transport in Clouds

A Talk at the
International EIKE Climate and Energy Conference
Vienna, Austria
15 June, 2024

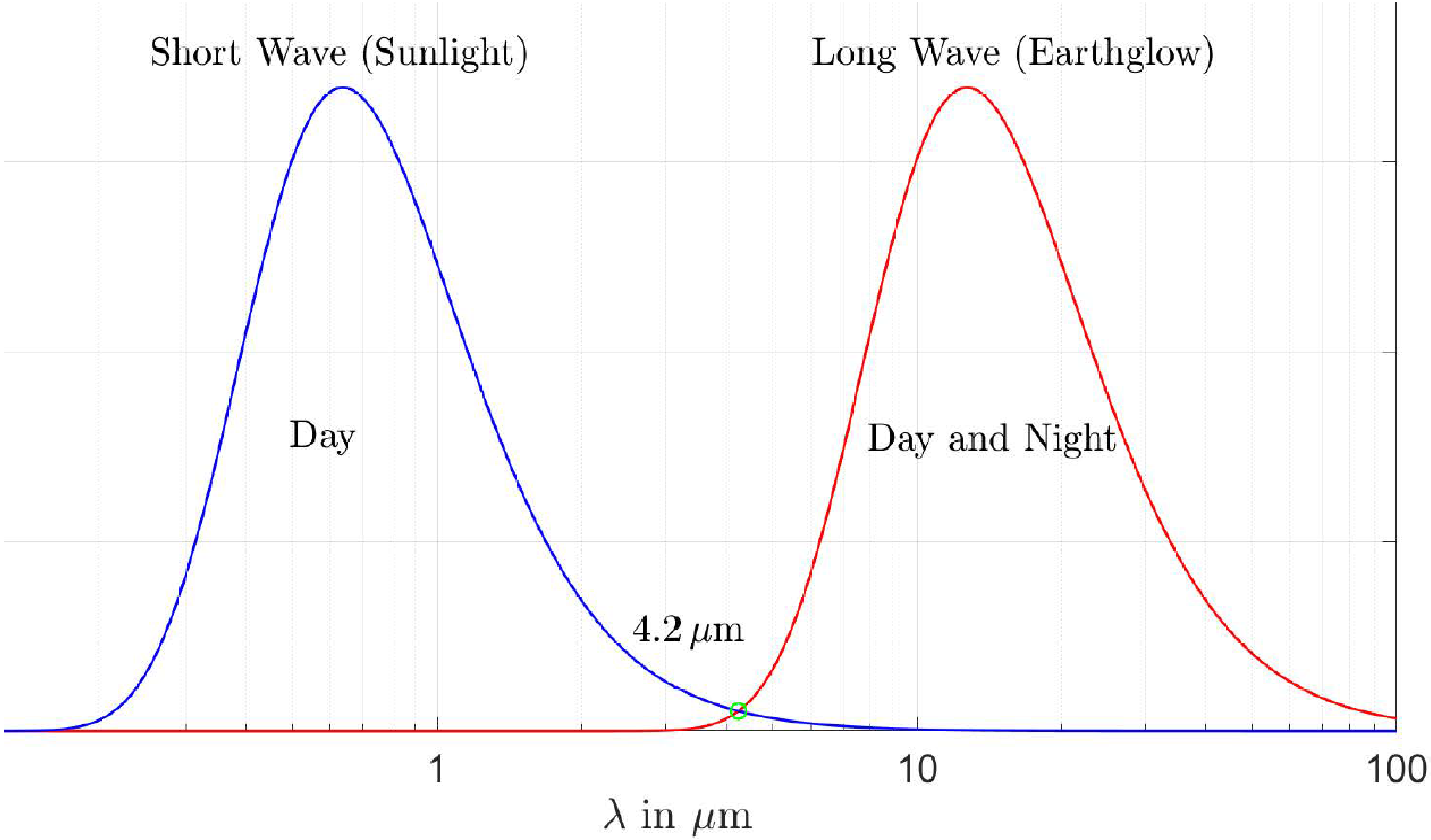
by William Happer
Cyrus Fogg Brackett Professor of Physics, Emeritus
Princeton, University

Leslie's
Aethrioscope



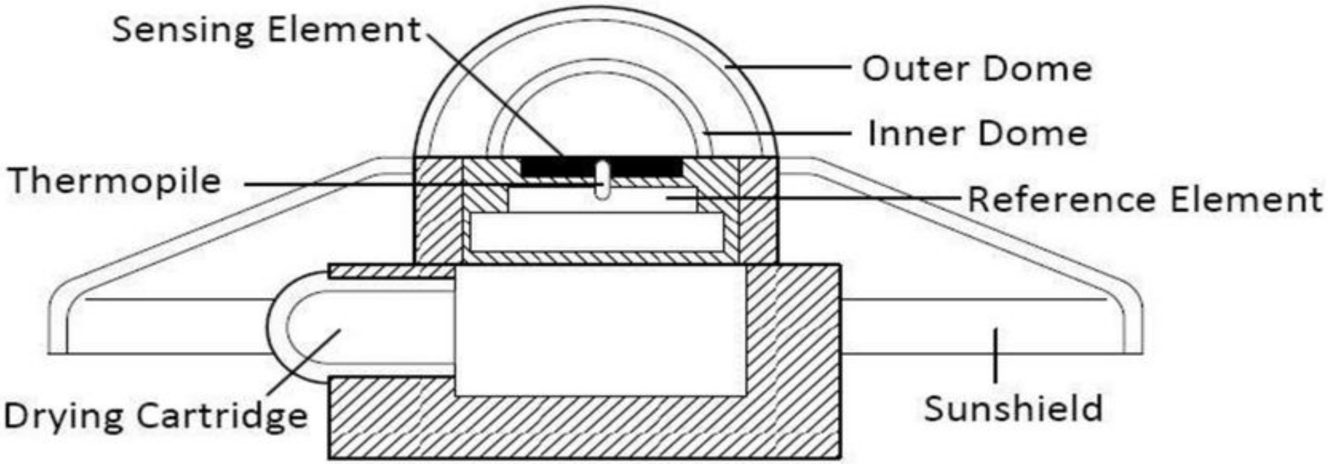
"The sensibility of the instrument is very striking, for the liquor incessantly falls and rises in the stem with every passing cloud. In fine weather, the aethrioscope will seldom indicate a frigorific impression of less than 30 or more than 80 millesimal degrees. If the sky become overclouded, may be reduce to as low as 15^{o} or even 5^{o} when the congregated vapours hover on the hilly tracts."

John Leslie
Scottish Physicist
1766-1832



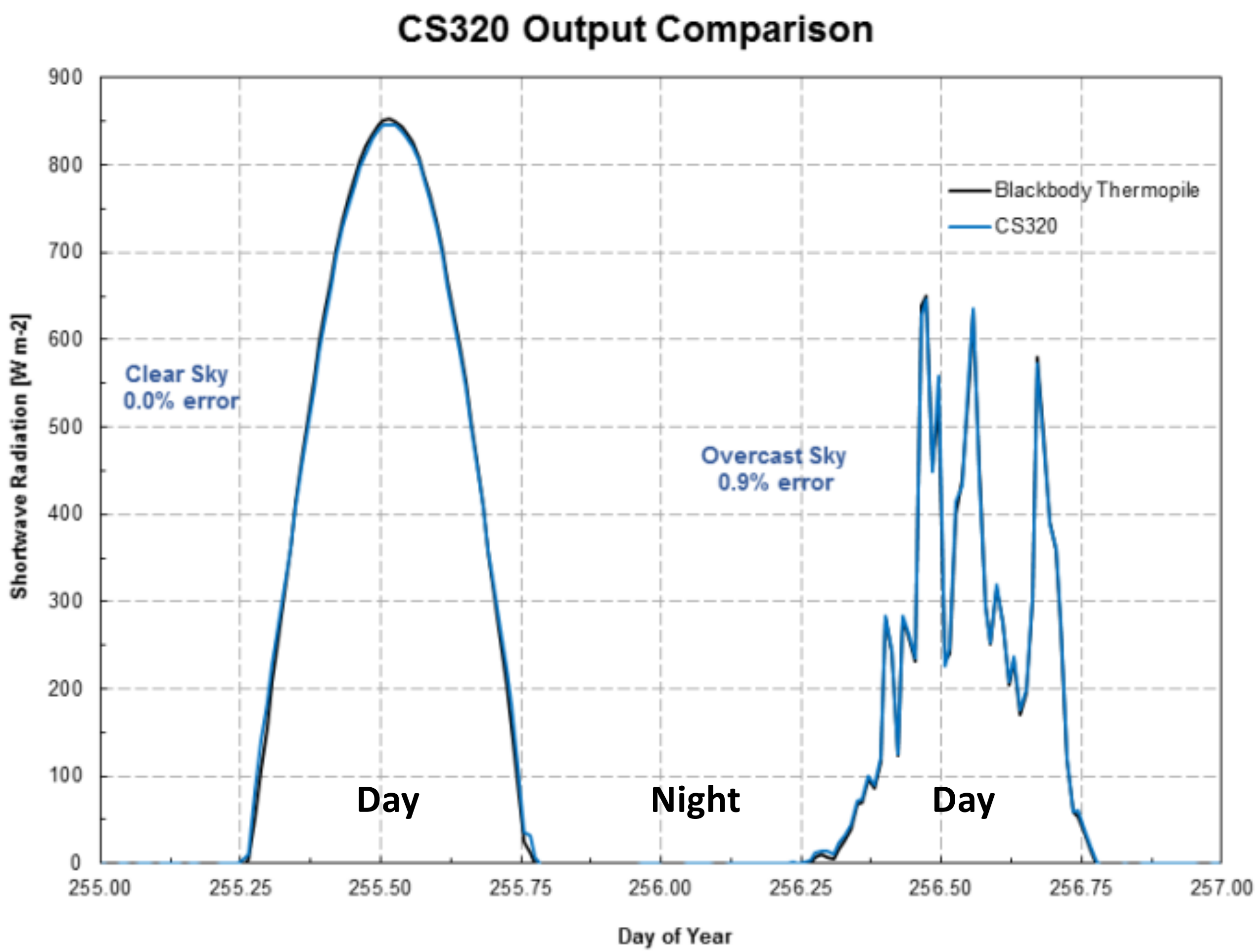
Short Wave (Sunlight)
Long Wave (Earthglow)
Day
Day and Night
4.2 μm
1
10
100
λ in μm

A Typical Pyranometer



Pyranometers are used to measure **global** and **diffuse** solar radiation (from the halfspace). The **thermopile** is composed of several thermocouples, connected in series. The output is a voltage proportional to the temperature difference between the **black surface** of the sensor element and the housing as **reference**. Two **quartz domes** and a ventilation system (shall) minimize external influences

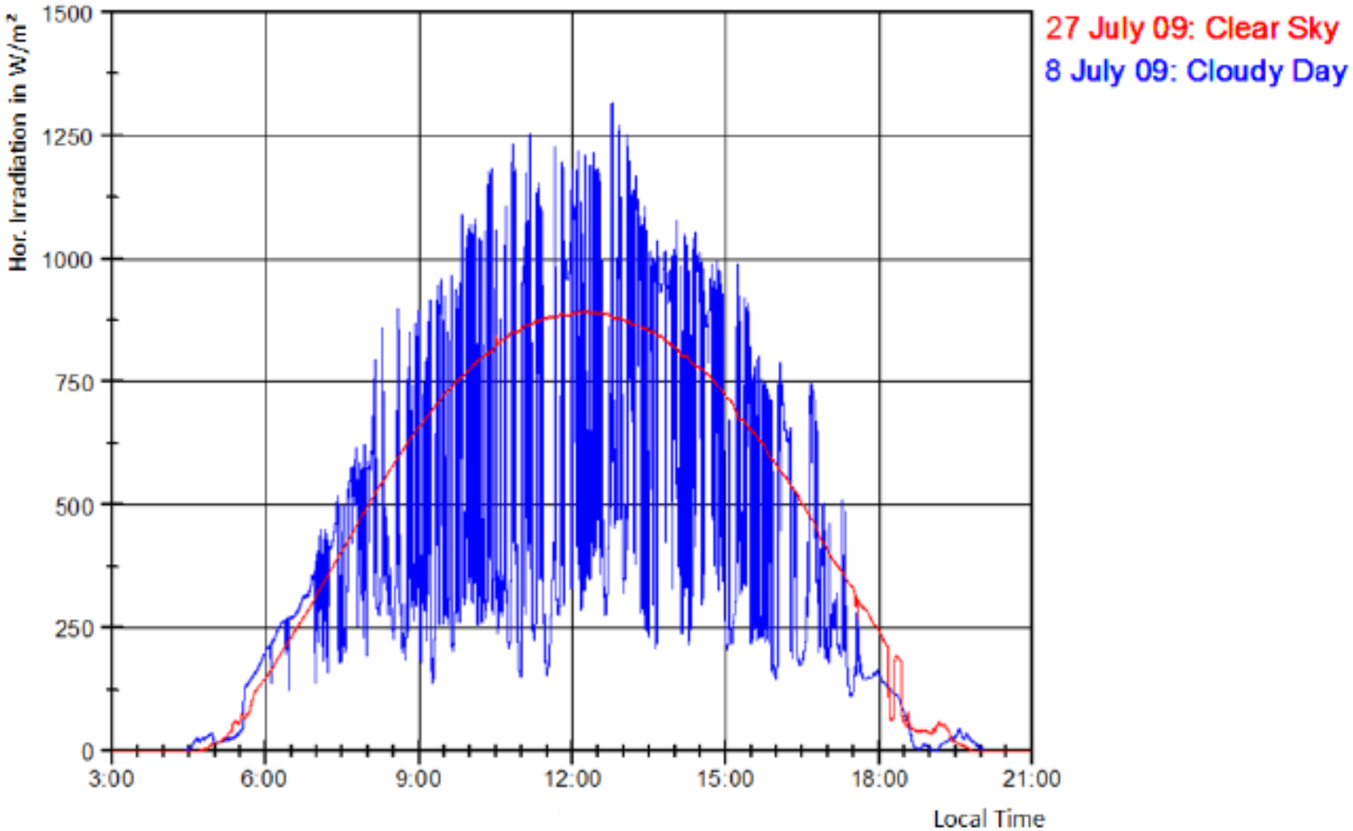
Pyranometer Measurements of Solar Flux on Earth's surface



https://www.campbellsci.ca/blog/measuring-sun-accurately-simply

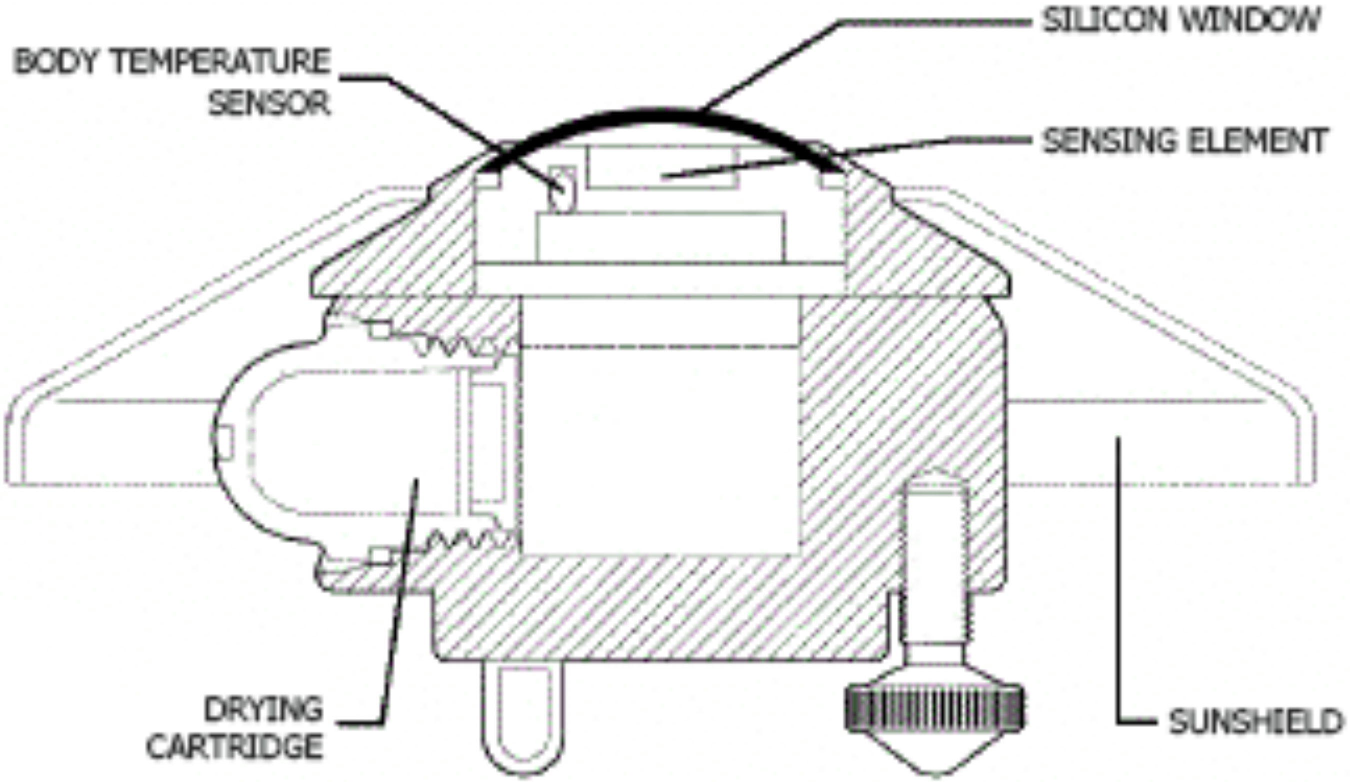
Cumulus Clouds Can Enhance Solar Irradiance on Earth's Surface

Kipp & Zonen CMP22 Pyranometer

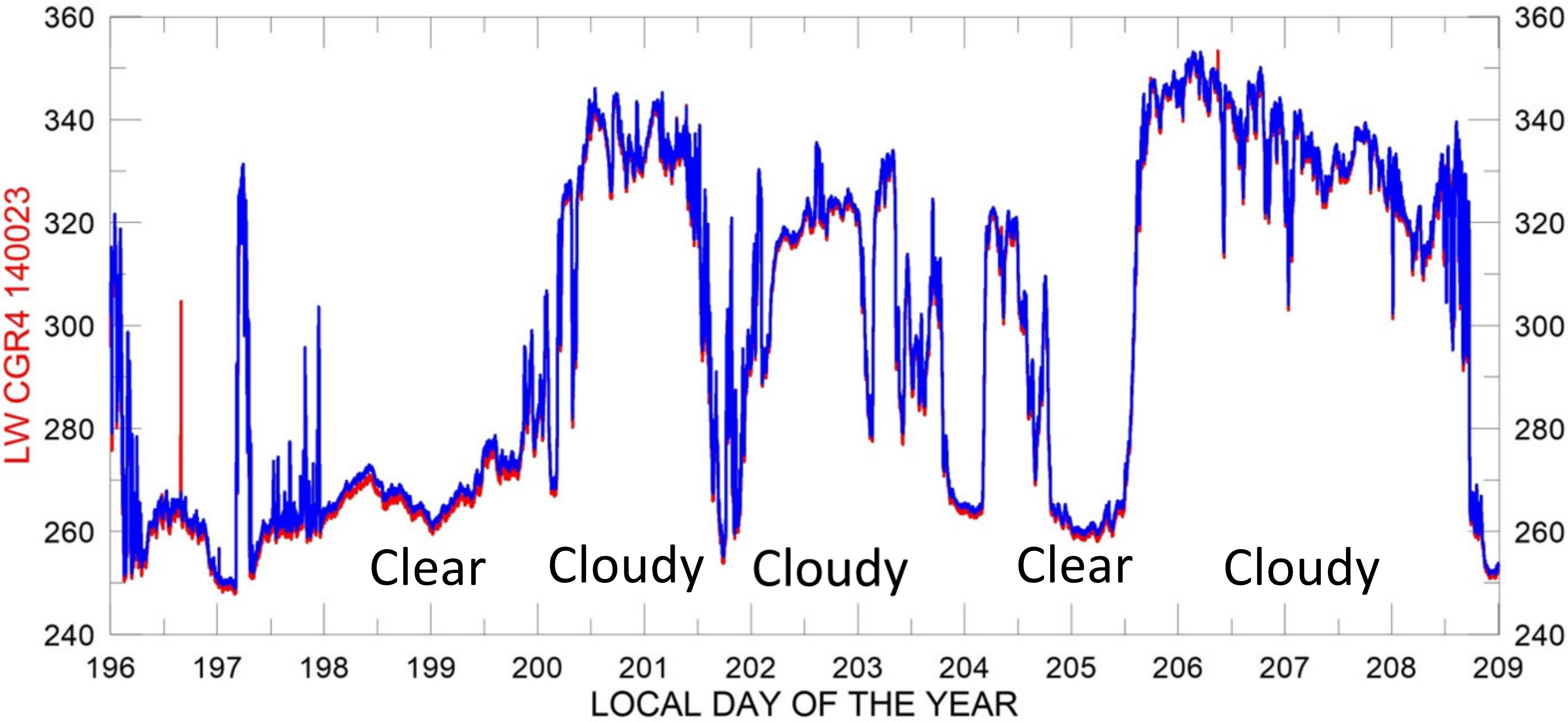


https://www.researchgate.net/publication/237353475_Systematic_Analysis_of_Meteorological_Irradiation_Effects/figures?lo=1

A "Solar Blind" Pyrgeometer to Measure Downwelling Thermal Radiation Flux from Greenhouse Gases and Clouds

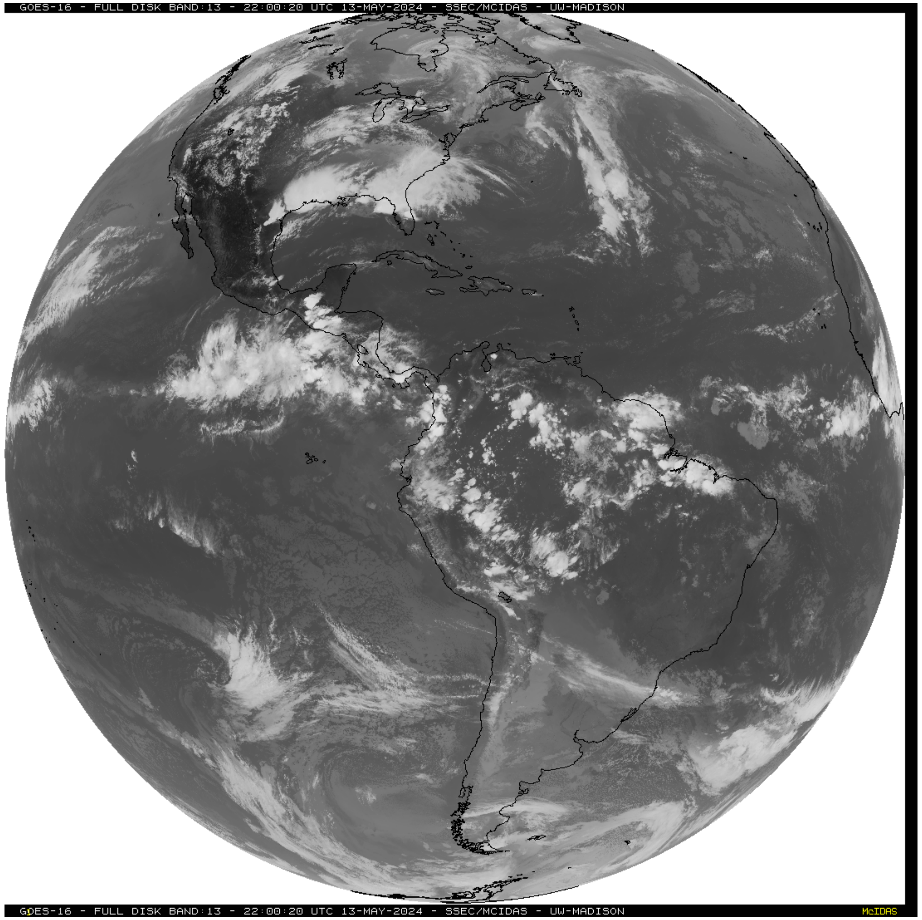


Thermal Downwelling Pyrgeometer Measurements in Thule (W m^{-2})



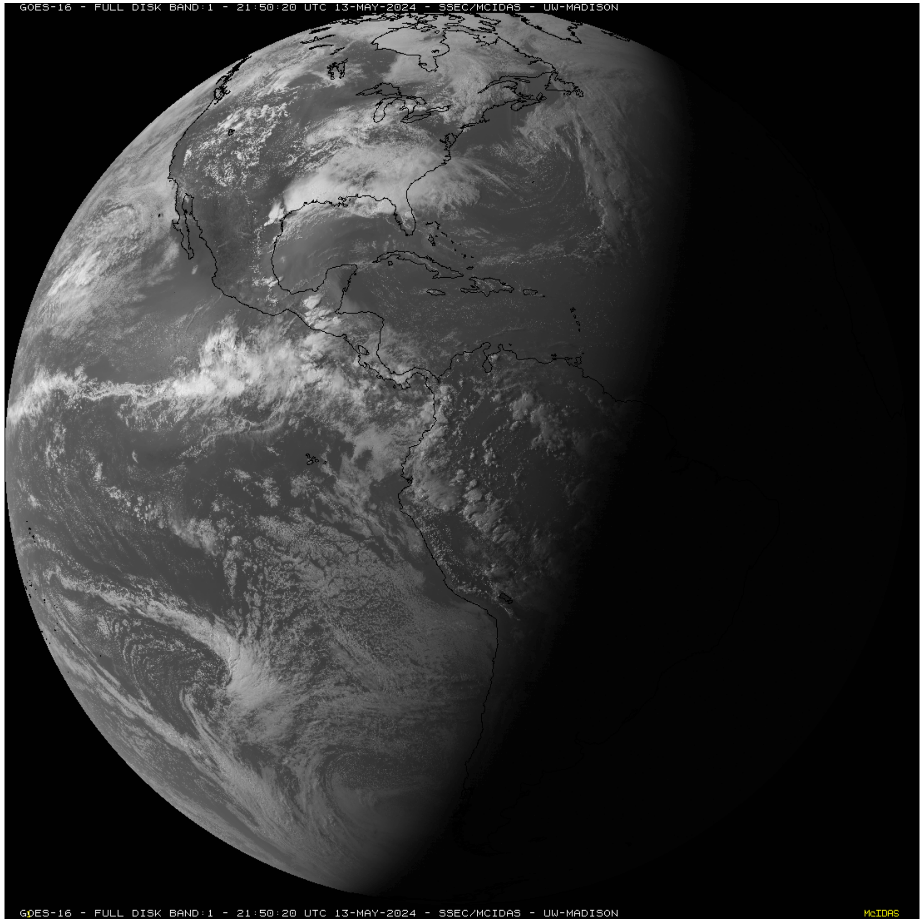
https://www.thuleatmos-it.it/instruments/radiometers/index.php

Earth glowing in the dark at a wavelength of 10.3 μm. The left, nighttime side is just as bright as the right sunlit side. White cloud tops are cold and emit very little radiation. Warmer land and oceans emit copious radiation.



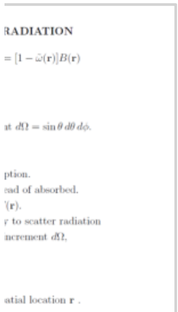
https://www.ssec.wisc.edu/data/geo/#/animation

Reflected blue sunlight of wavelength 0.47 μm, recorded at the same time from the same satellite. White cloud tops reflect lots of sunlight. Land and oceans reflect less.



6:12 pm Princeton Time, 13 May, 2024

Modelled Spectra Can Hardly Be Distinguished From Measured Spectra.



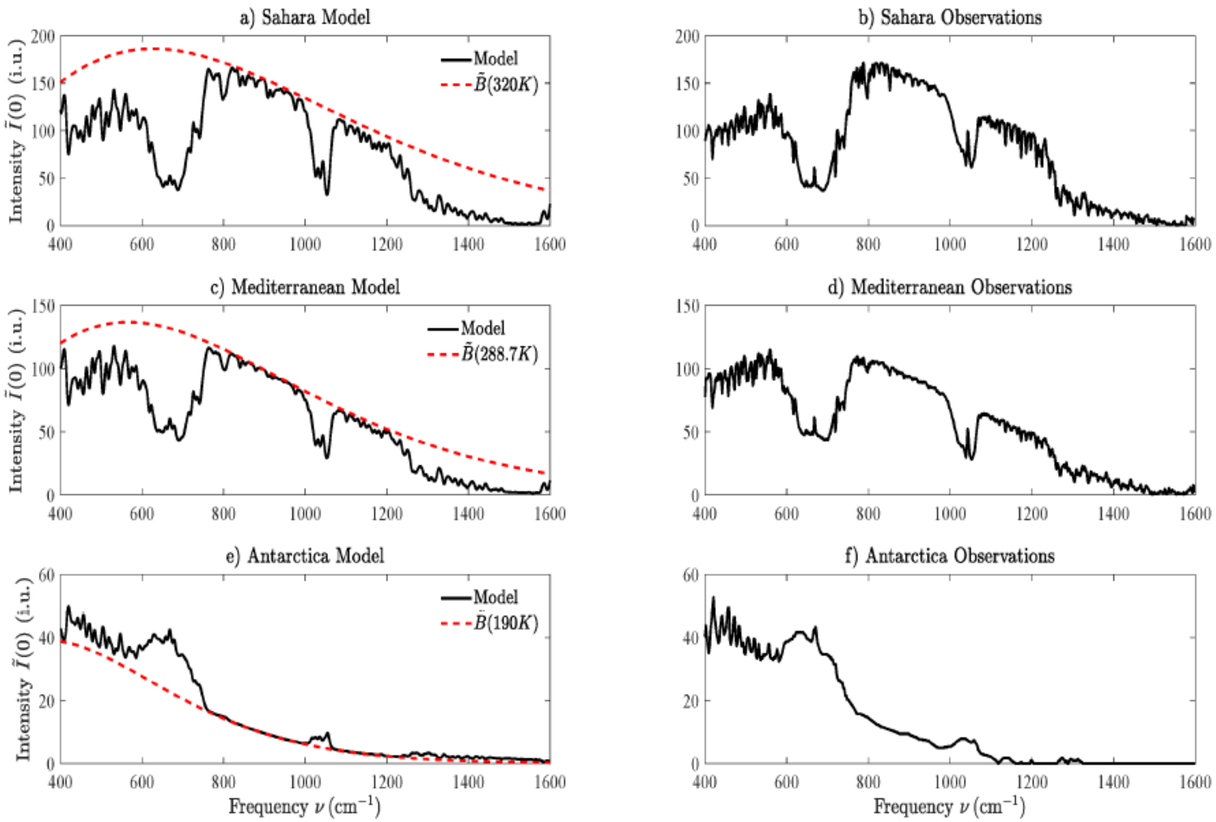


Figure 15: Vertical intensities $\tilde{I}(0)$ at the top of the atmosphere observed with a Michelson interferometer in a satellite [44], and modeled with (27): over the Sahara desert, the Mediterranean and Antarctica. The intensity unit is 1 i.u. = 1 mW m^{-2} cm sr^{-1}. Radiative forcing is negative over wintertime Antarctica since the relatively warm greenhouse gases in the troposphere, mostly CO_2, O_3 and H_2O, radiate more to space than the cold ice surface, at a temperature of $T = 190$ K, could radiate through a transparent atmosphere.

Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases

W. A. van Wijngaarden[1] and W. Happer[2]

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June 8, 2020

https://arxiv.org/pdf/2006.03098

Radiation inside and outside of clouds can be modelled very accurately with the formidable "Equation of Transfer"

$$\frac{1}{\alpha(\mathbf{r})}(\hat{\mathbf{n}} \cdot \nabla)I(\mathbf{r},\hat{\mathbf{n}}) + I(\mathbf{r},\hat{\mathbf{n}}) - \frac{\tilde{\omega}(\mathbf{r})}{4\pi}\int_{4\pi} d\Omega' p(\mathbf{r},\hat{\mathbf{n}},\hat{\mathbf{n}}')I(\mathbf{r},\hat{\mathbf{n}}') = [1-\tilde{\omega}(\mathbf{r})]B(\mathbf{r})$$

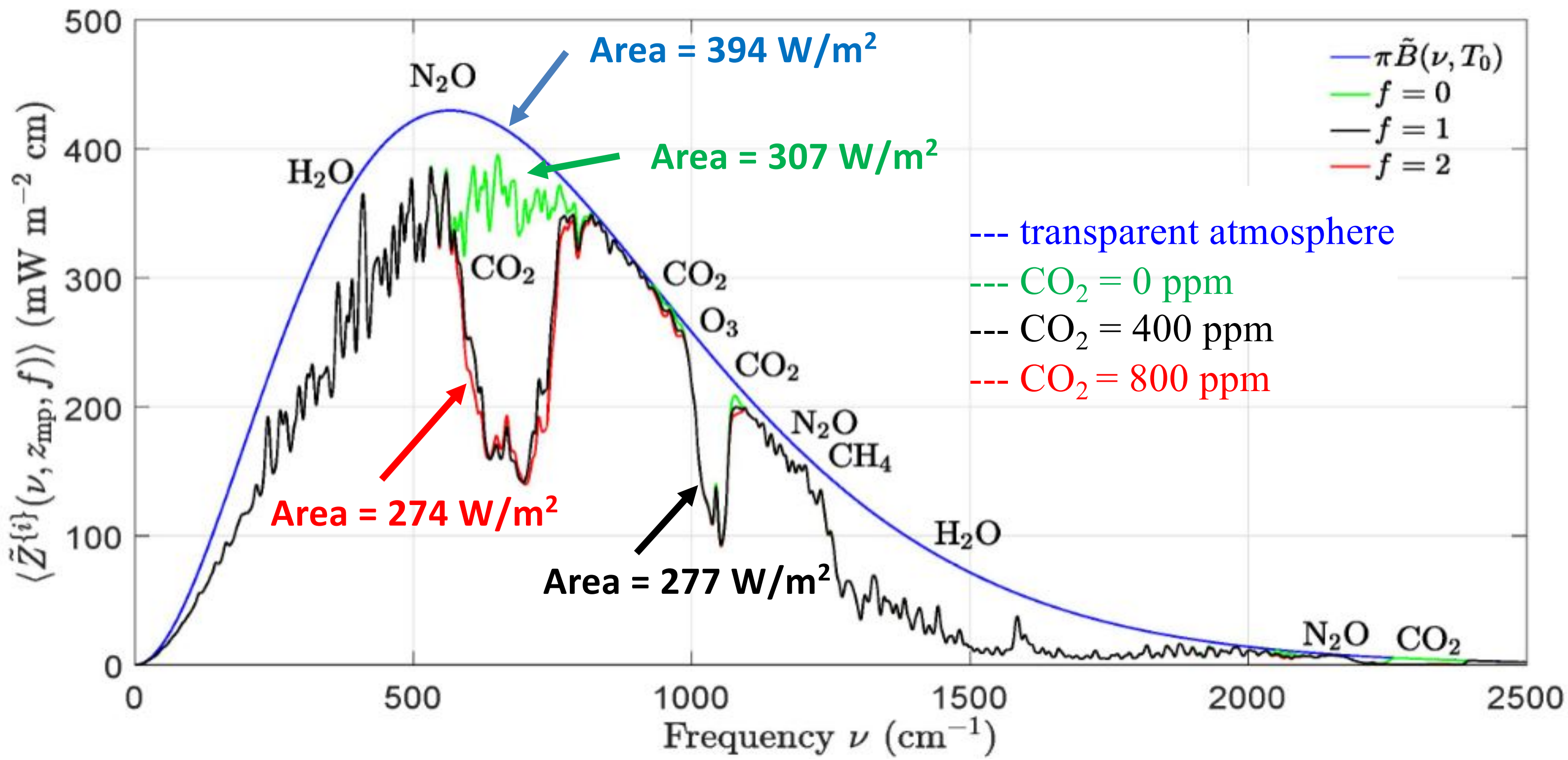
This integro differential equation is too complicated discuss in detail today, but I will try to give the flavor of how to solve it.

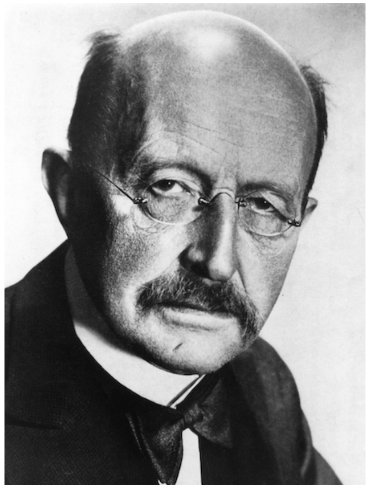
For more details, see these links to papers by W. van Wijngaarden and W. Happer

http://arxiv.org/abs/2205.09713 2n-Stream Radiative Transfer

http://arxiv.org/abs/2310.10622 Radiative Transfer in Cloud Layers

Thermal radiation to space from the Earth, with a surface temperature of 15.5 C and with greenhouse gases is the area under the jagged black "Schwarzschild" curve. This is only about 70% of what it would be without greenhouse gases, the area under the smooth blue "Planck" curve. The Sun heats the Earth and greenhouse gases hinder the cooling.





Max Planck
1858-1947

Karl Schwarzschild
1873-1916

EQUATION OF TRANSFER
FOR TIME-INDEPENDENT MONOCHROMATIC RADIATION

$$\frac{1}{\alpha(\mathbf{r})}(\hat{\mathbf{n}}\cdot\nabla)I(\mathbf{r},\hat{\mathbf{n}}) + I(\mathbf{r},\hat{\mathbf{n}}) - \frac{\tilde{\omega}(\mathbf{r})}{4\pi}\int_{4\pi} d\Omega' p(\mathbf{r},\hat{\mathbf{n}},\hat{\mathbf{n}}')I(\mathbf{r},\hat{\mathbf{n}}') = [1-\tilde{\omega}(\mathbf{r})]B(\mathbf{r})$$

Independent variables

$\mathbf{r}$ = Spatial location in atmosphere; $\nabla = \partial/\partial\mathbf{r}$.

$\hat{\mathbf{n}}$ = Directional unit vector, centered in solid-angle increment $d\Omega = \sin\theta \, d\theta \, d\phi$.

"Knowns" at spatial location r

$\alpha(\mathbf{r})$ = Attenuation coefficient from scattering and absorption.

$\tilde{\omega}(\mathbf{r})$ = Single scattering albedo = fraction scattered instead of absorbed.

$B(\mathbf{r})$ = Planck intensity; depends on local temperature $T(\mathbf{r})$.

$p(\mathbf{r},\hat{\mathbf{n}},\hat{\mathbf{n}}')$ = Phase function; $p(\mathbf{r},\hat{\mathbf{n}},\hat{\mathbf{n}}')d\Omega/4\pi$ is the probability to scatter radiation from the initial direction $\hat{\mathbf{n}}'$ into the solid-angle increment $d\Omega$, centered on the final direction $\hat{\mathbf{n}}$.

Unknown

$I = I(\mathbf{r},\hat{\mathbf{n}})$ = Intensity or radiance along unit vector $\hat{\mathbf{n}}$ at spatial location $\mathbf{r}$.

2N-STREAM RADIATION TRANSFER THEORY

1. ASSUME AXIAL SYMMETRY (CLOUD LAYERS)

$$I(\mathbf{r}, \hat{\mathbf{n}}) \rightarrow I(z, \mu) \quad \text{where} \quad z = \text{altitude} \quad \text{and} \quad \mu = \cos\theta = \text{direction cosine}$$

2. USE 2n GAUSS-LEGENDRE SAMPLE INTENSITIES

$$I(z, \mu) \rightarrow I(z, \mu_i) \quad \text{where} \quad P_{2n}(\mu_i) = 0$$

The Gauss-Legendre direction cosines μ_i are the $2n$ roots of the Legendre polynomial $P_{2n}(\mu)$. Unlike the evenly spaced Shannon-Nyquist time samples of a band-limited communication signal, the μ_i are more closely spaced near $\mu = \pm 1$

3. DISTINGUISH INTERNAL FROM EXTERNAL RADIATION

$$\dot{I}(z, \mu_i) \;=\; \text{radiation thermally emitted by molecules and particulates}$$
$$\ddot{I}(z, \mu_i) \;=\; \text{radiation from external sources like sunlight}$$

4. USE 2n x 2n SCATTERING MATRICES $\mathcal{S}$ AND EMISSION MATRICES $\mathcal{E}$

$$\mathcal{S} + \mathcal{E} = 1 \quad \text{Kirchhoff's law}$$

$\dot{I}$ = THERMAL EMISSION: Visible light is emitted by very hot atoms or particulates, in this example by fireworks, but also by lightening, aurora, etc. Long wave infrared radiation is emitted by greenhouse gas molecules and particulates at normal atmospheric temperatures. Measured with PYRGEOMETERS.

$\ddot{I}$ = SCATTERED white sunlight from particulates of water or ice (clouds), and blue, Rayleigh-scattered sunlight from N_2 and O_2 in cloud-free air. Scattered long wave infrared radiation comes only from particulates, for example, the water or ice particulates of clouds. There is negligible scattering of long wave radiation by molecules. Measured with PYRANOMETERS.

The basic idea of 2n-stream radiative transfer theory goes back to a paper, written in 1943 by Gian Carlo Wick, Über ebene Diffusionsprobleme, Zeit. Phys., **121**, 702 (1943). Wick's two key steps were:

- Consider only axially symmetric radiation transfer
- Replace the scattering integral with a sum on $2n$ samples, a Gaussian quadrature

→ Axial symmetry **→ Gaussian quadrature**

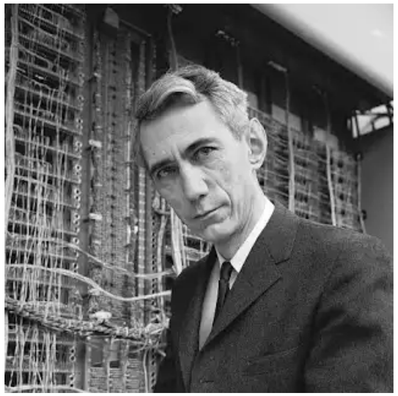
$$\int_{4\pi} d\Omega' p(\hat{\mathbf{n}}, \hat{\mathbf{n}}') I(\hat{\mathbf{n}}') \to 2\pi \int_{-1}^{1} d\mu' p(\mu, \mu') I(\mu') \to 2\pi \sum_{i'=1}^{2n} p(\mu_i, \mu_{i'}) w_i I(\mu_{i'})$$

Wick's sampling is closely analogous to Shannon-Nyquist sampling of communication signals. But unlike the equally-weighted Shannon-Nyquist sample times, each of the $2n$ **Gauss-Legendre sample direction cosines** μ_i **has a different weight** w_i **given in terms of the Legendre polynomials** P_l **by**

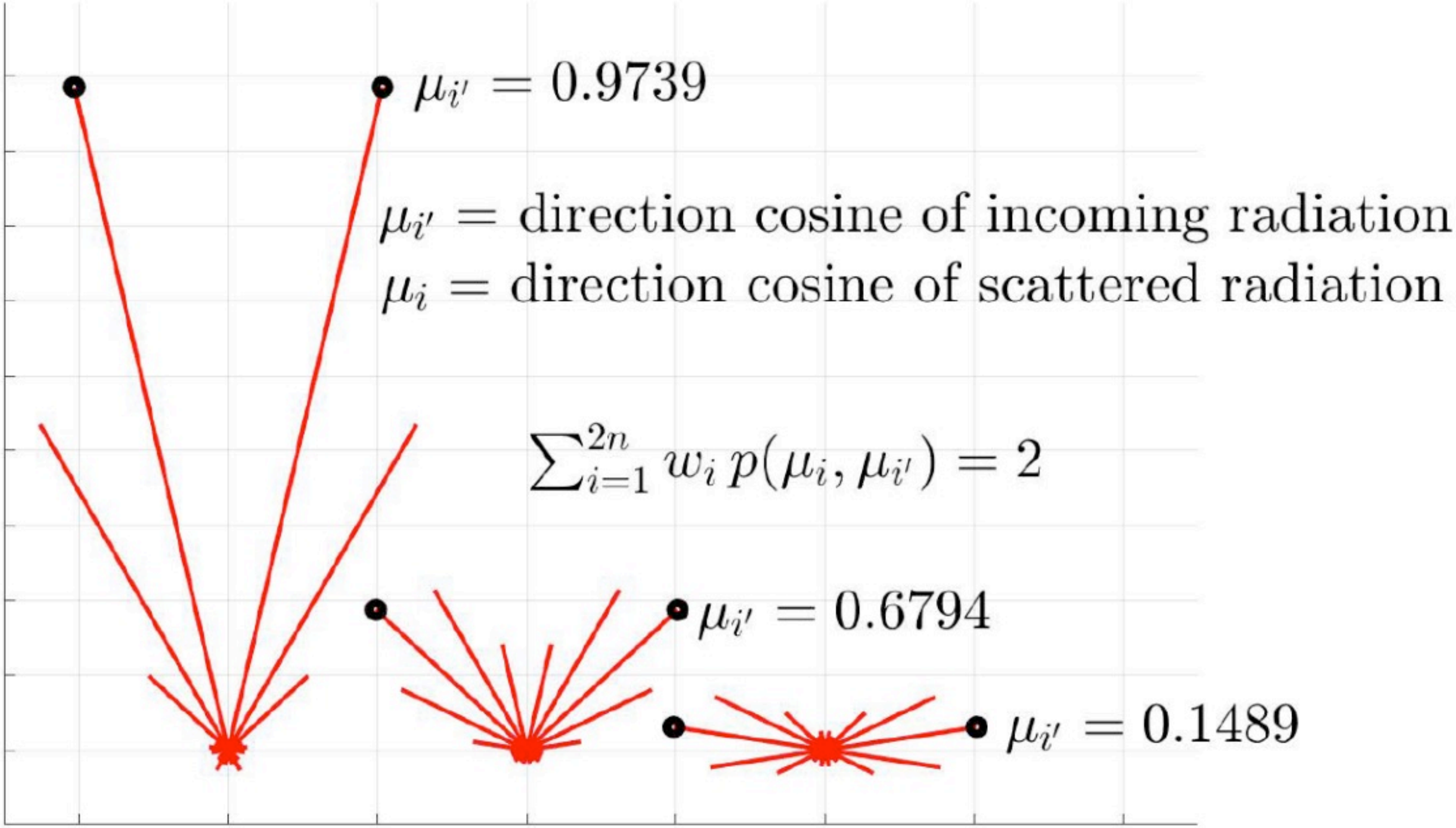
$$\frac{1}{w_i} = \sum_{l=0}^{2n-1} \frac{2l+1}{2} P_l^2(\mu_i)$$

Gian Carlo Wick
1909-1992

Claude Shannon
1916-2001



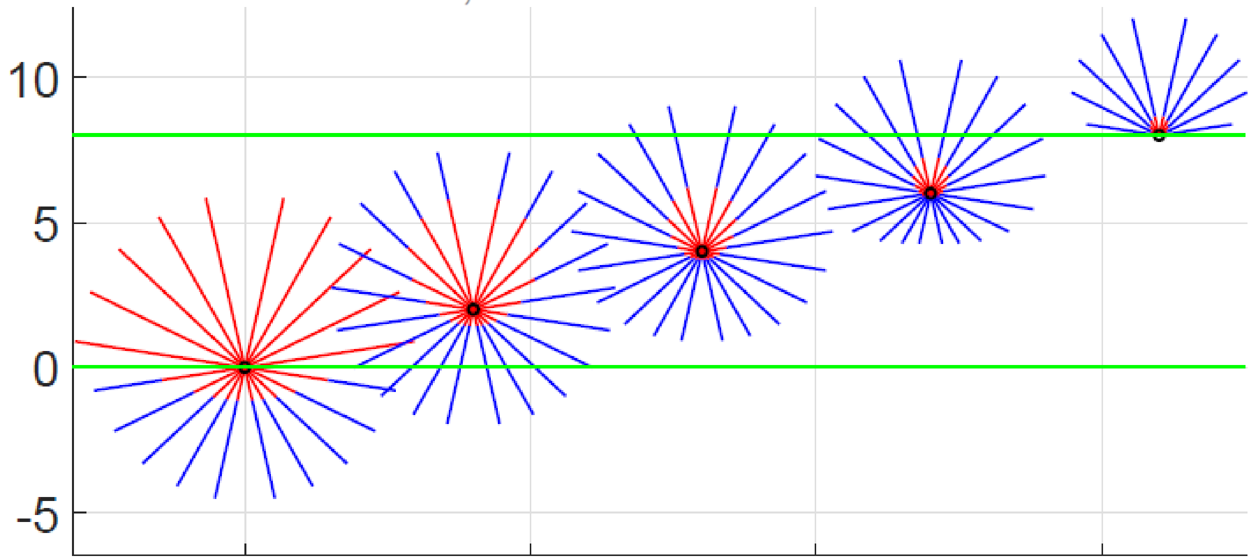
Scattering Phase Function $p(\mu_i, \mu_{i'})$ for Cloud Particulates



GREEN LINES SHOW THE BOTTOM AND TOP OF A CLOUD LAYER AT OPTICAL DEPTHS $\tau = 0$ AND $\tau = 8$

BLUE RAYS SHOW INTENSITIES $\dot{I}(\tau, \mu_i)$ THERMALLY GENERATED BY ISOTHERMAL CLOUD PARTICULATES WITH A PLANCK INTENSITY B

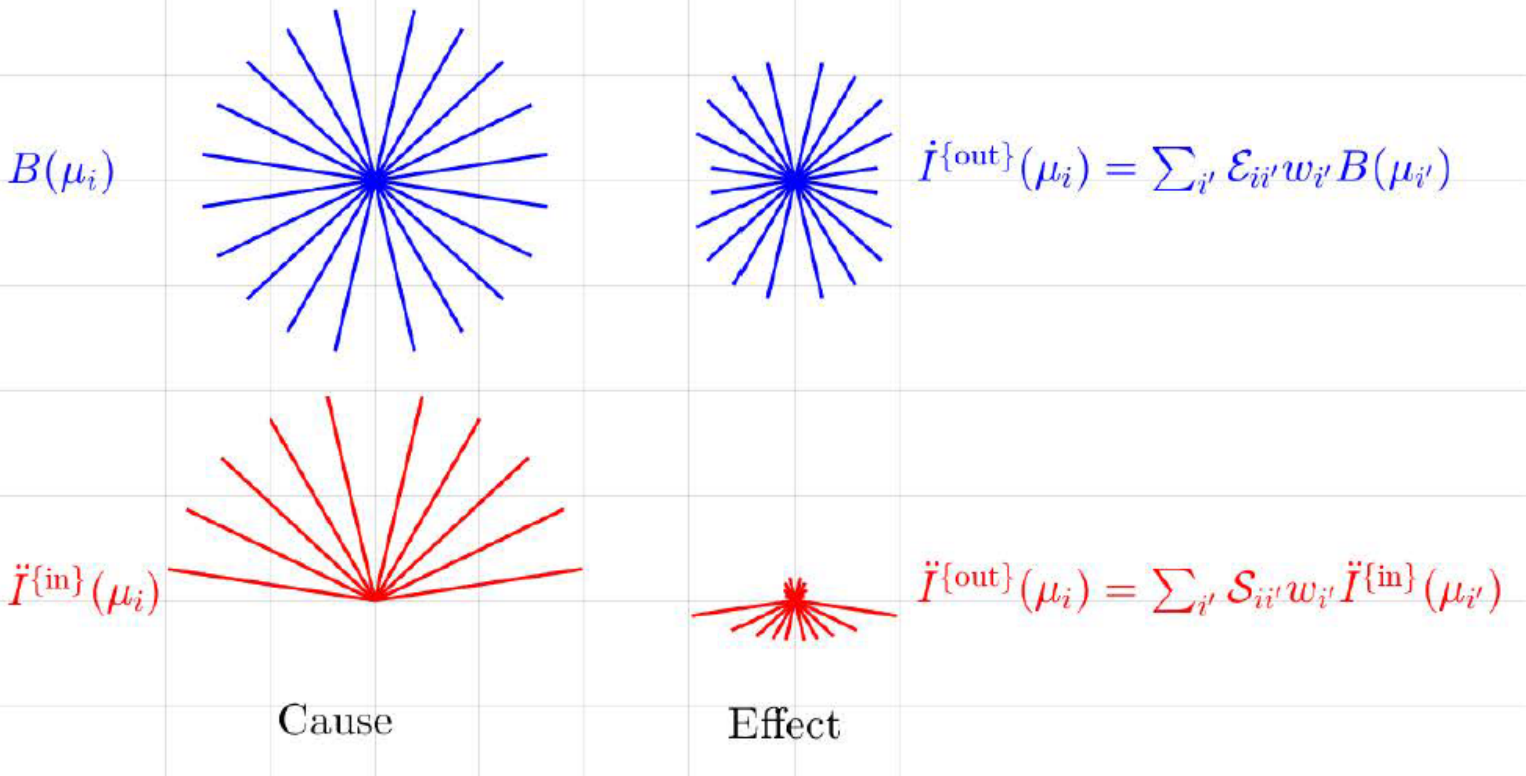
RED RAYS SHOW INCIDENT AND SCATTERED INTENSITIES $\ddot{I}(\tau, \mu_i)$ FROM A BLACK BODY LOCATED BELOW THE CLOUD. THE BLACK BODY IS WARMER THAN THE CLOUD AND HAS A 20% LARGER PLANCK INTENSITY, $1.2B$



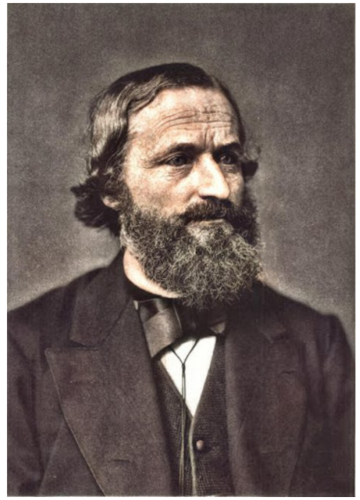
http://arxiv.org/abs/2205.09713

Kirchhoff's Law: $\mathcal{S}_{ii'} + \mathcal{E}_{ii'} = \delta_{ii'}$

Cloud Scattering Matrix $\mathcal{S}$ + Cloud Emissivity Matrix $\mathcal{E}$ = Unit Matrix 1



Gustav Kirchhoff
1824-1887



The Blue Marble. A photograph of Earth and its clouds taken by Lunar astronaut Harrison Schmitt, 7 December, 1972.

Take away messages:

- CO_2, carbon-dioxide is not the control knob of Earth's climate.
- Clouds and water vapor are much more important.
- Clouds can be quantitatively modeled with 2n-Stream Radiative Transfer Theory.