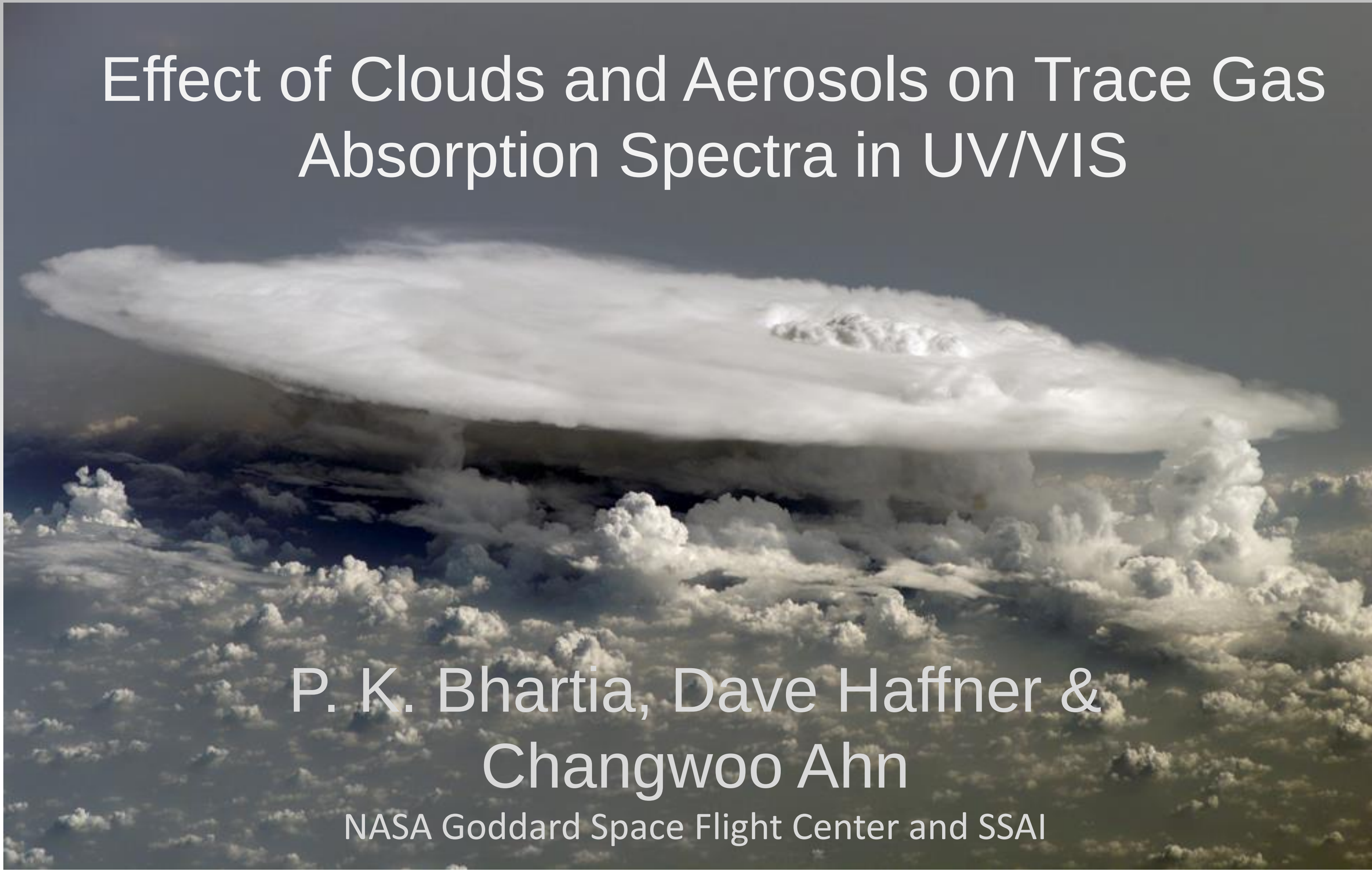

# Effect of Clouds and Aerosols on Trace Gas Absorption Spectra in UV/VIS

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# Outline

- Key Effects of Clouds
- Optical Centriod Pressure (OCP)
- Raman
- Cloud Radiative Fraction (CRF)
- Cloud Models

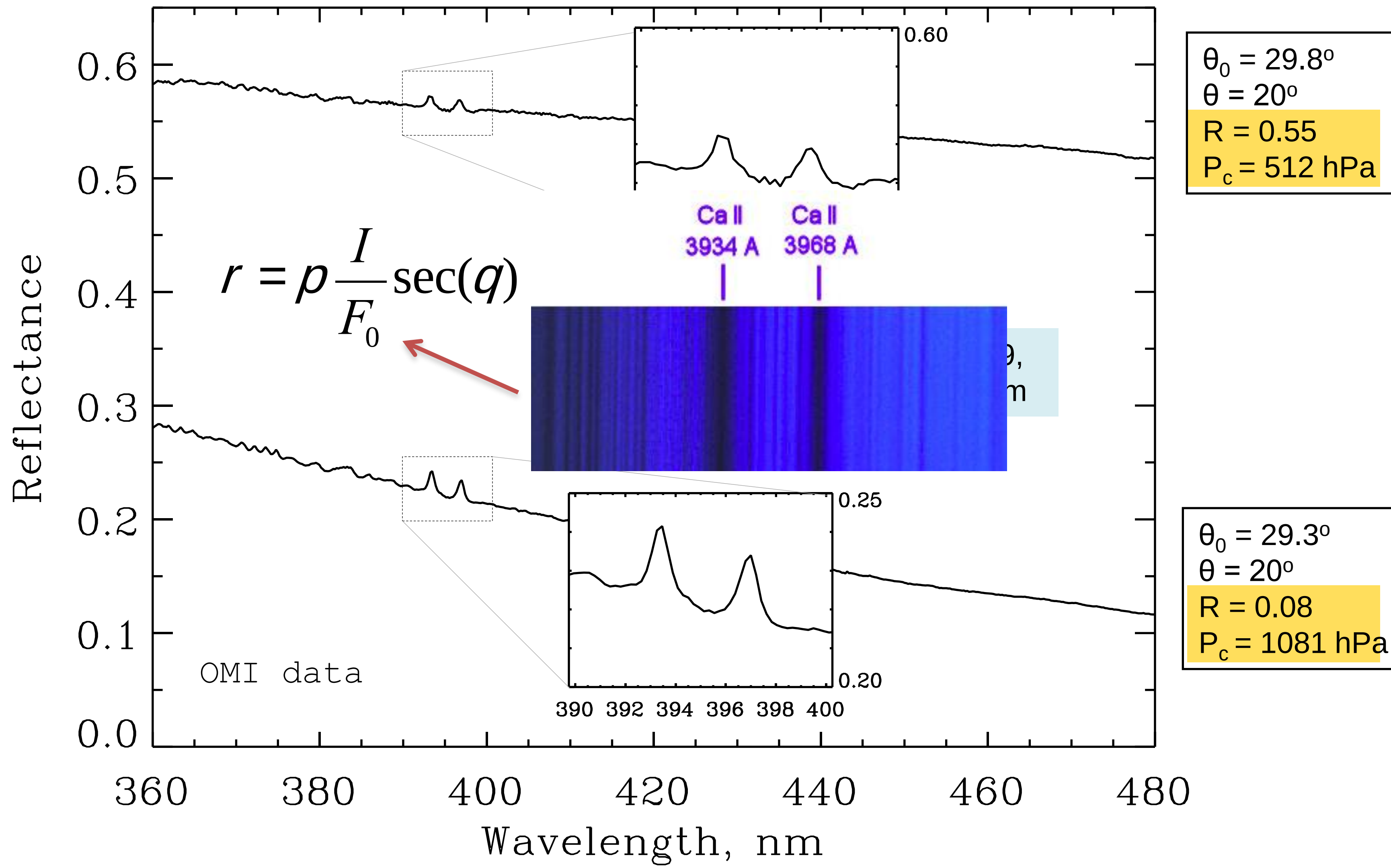
# Key Effects

- Rayleigh scattering is reduced
  - Effect depends on cloud fraction and reflectivity but not on cloud height.
- Ring Effect (Raman scattering) is reduced
  - Effect depends cloud fraction, reflectivity and cloud optical centroid pressure (OCP).
- Airmass Factor (AMF) is usually reduced
  - Effect depends on cloud radiance fraction (CRF) and cloud OCP.

$$I = I_0 \, e^{-mt}$$

$$\text{AMF: } m = -\frac{1}{t}\ln\left(\frac{I}{I_0}\right) \text{ or } \; m = -\frac{\partial \ln I}{\partial t}$$

# Effect of Rayleigh & Raman Scattering on UV/VIS spectra




Key conclusion: Clouds reduce the spectral dep. of TOAR and Ring

# How clouds affect to gas absorption at different $\lambda$s

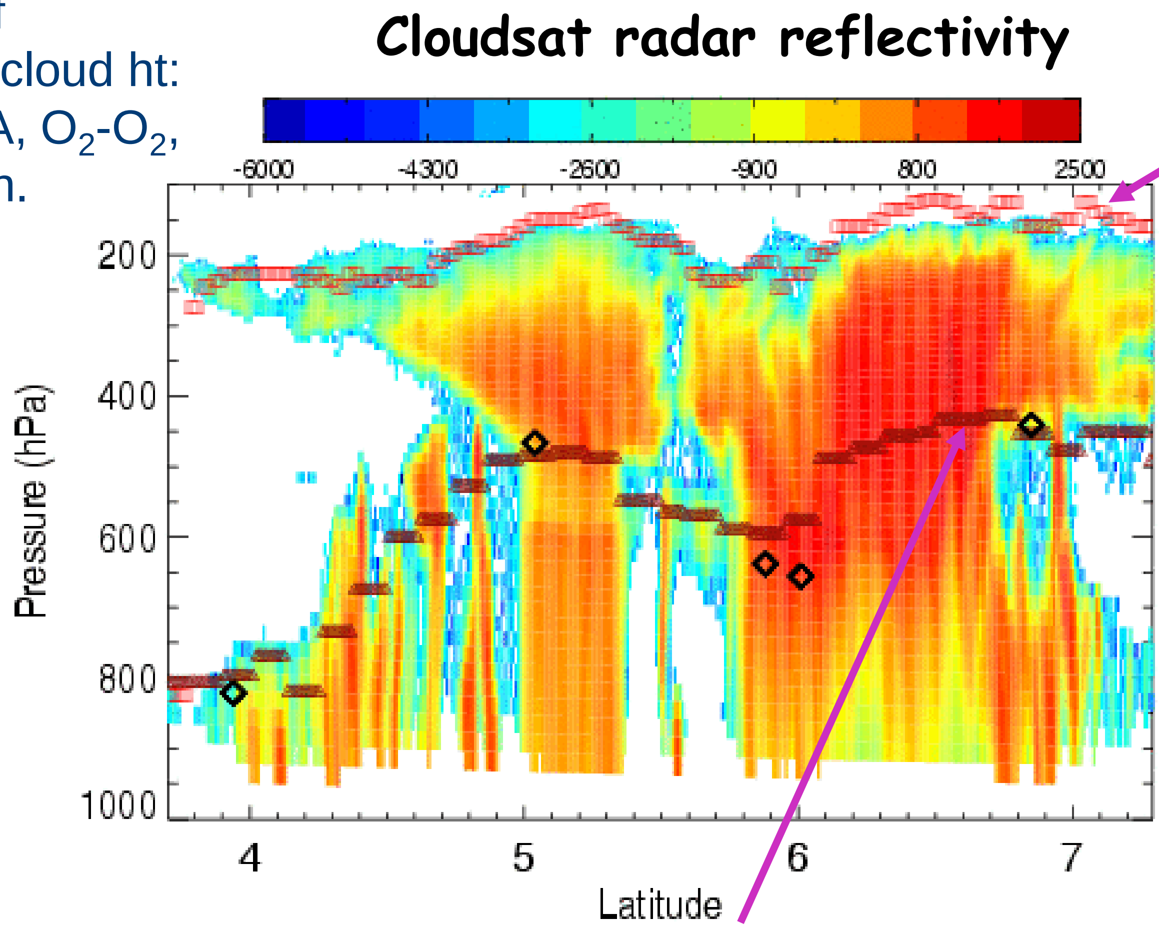
- Clouds droplets absorb thermal IR radiation. Therefore, radiation is not sensitive to gases below the cloud top, unless the cloud is optically thin.
- Clouds droplets do not absorb UV/VIS radiation. Therefore, radiation is sensitive to gases far below the cloud top, even when the cloud is optically very thick.  For thin clouds radiation is sensitive to trace gases below the cloud.

# What is Cloud Optical Centroid Pressure (OCP)?

- Mean photon path length for cloud layer
- OCP determines how much of the trace gas column a satellite instrument sees in presence of clouds, if the gas is well-mixed inside the cloud.
  - For a single layer cloud OCP is slightly below the cloud top.
  - For a vertically extended cloud, e.g., deep convective cloud, it is usually near the ice/water boundary.
  - For multi-layer clouds it is usually near the lower level clouds.

# Multi-phase Cloud Effects

There are 5 different methods of estimating cloud ht: 2 TIR, $O_2$-A, $O_2$-$O_2$, and Raman.



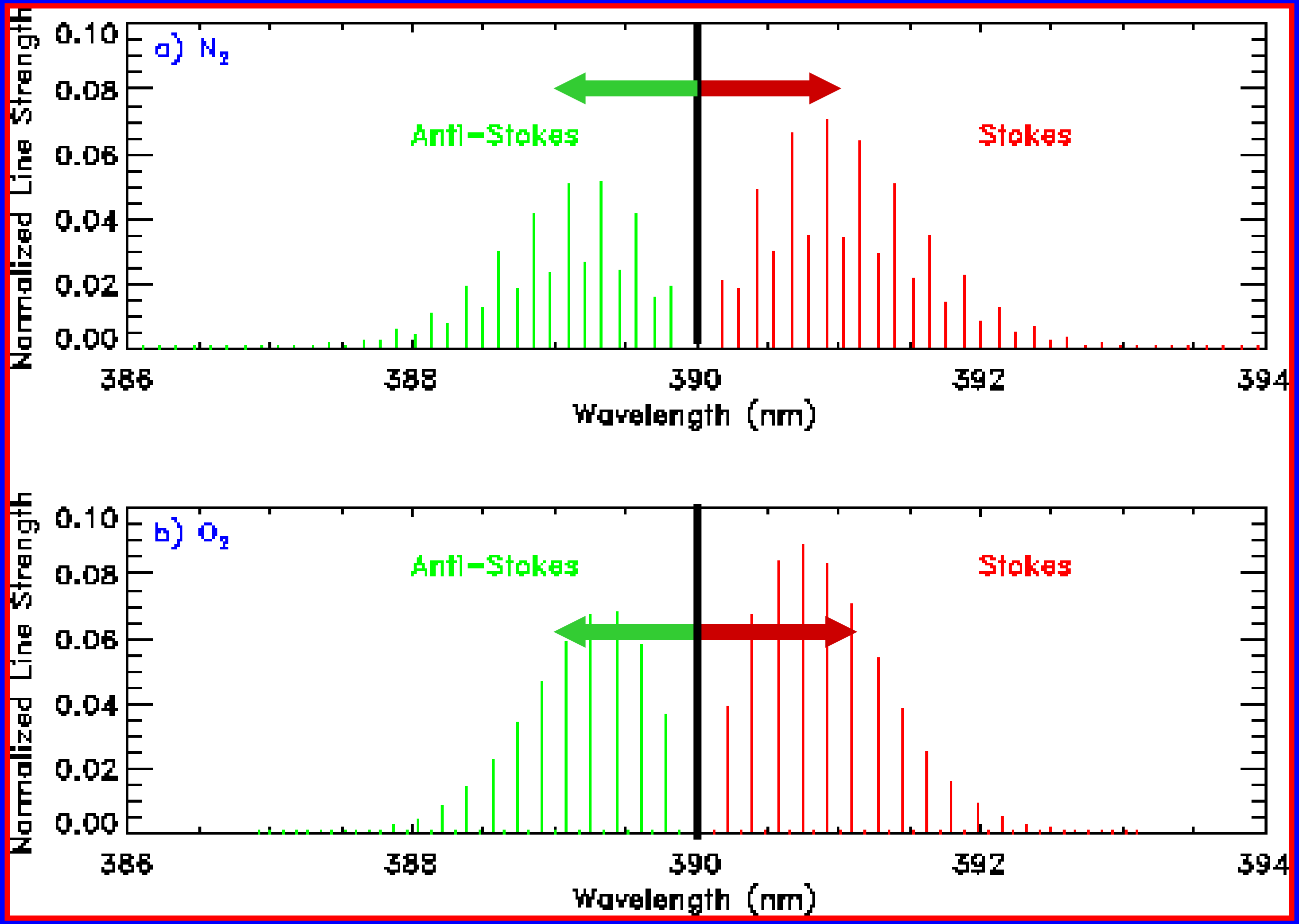

MODIS cloud-top press is insensitive to cloud vertical structure

Cloud Optical Centroid press calculated using OMI-measured Rot Raman Scattering is sensitive to cloud vert structure (ref : Vasilkov *et al*.,JGR, ’08)

# Methods of estimating Cloud OCP

- Rotation Raman Scattering (Ring Effect)
  - The technique works best at near UV wavelengths (345-355 nm) for relatively thick clouds ($\tau$>5 )
- $O_2$-$O_2$ dimer absorption
  - 477 nm band works best. Works better than Raman for thin clouds.
- $O_2$ Absorption
  - B-band probably works better than A-band over land

# Atmospheric Rotational-Raman scattering

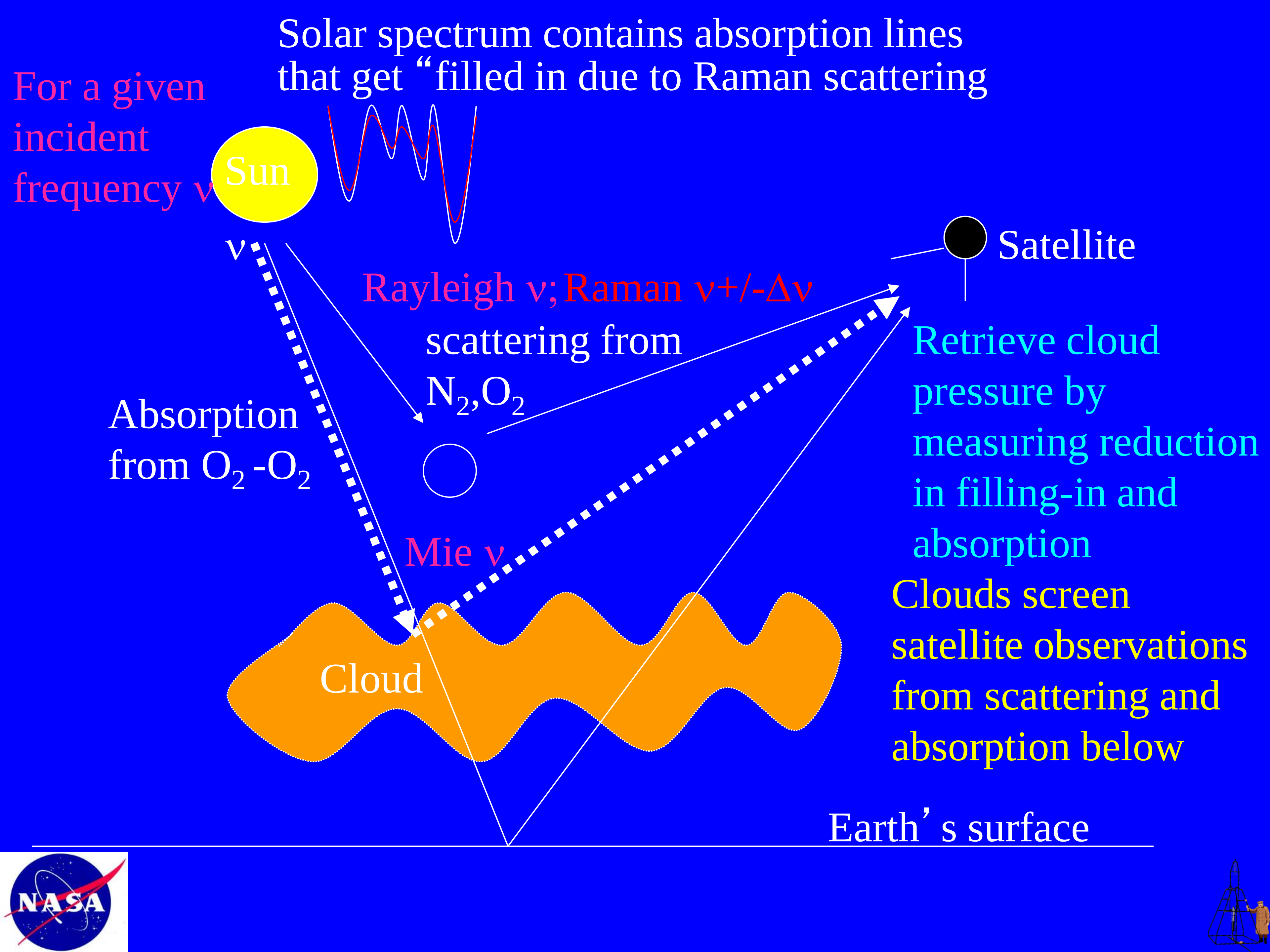



Energy transferred
to longer wavelengths

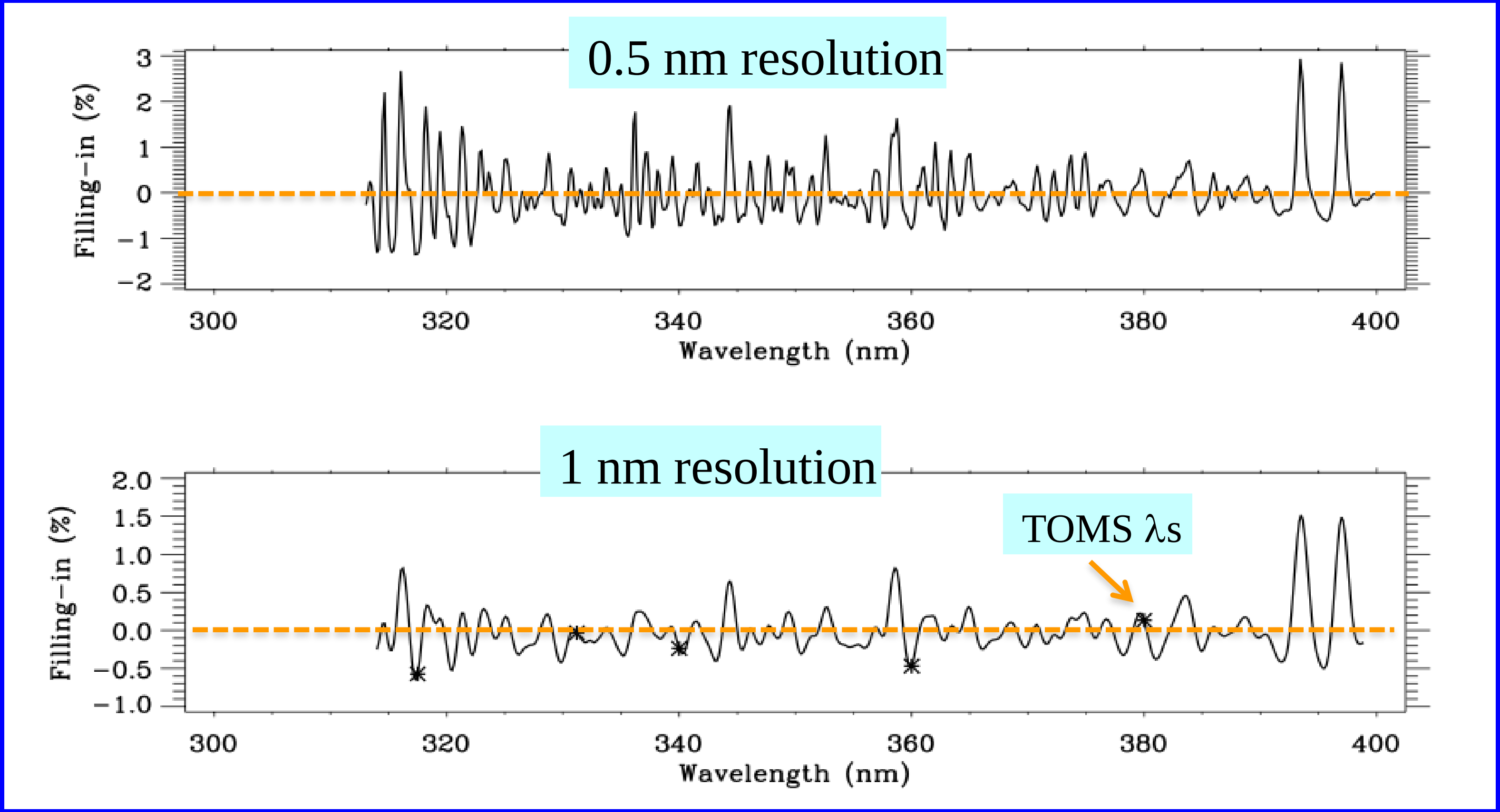
Energy transferred
to shorter wavelengths

Ex. Incident light at 390 nm (96% scattered elastically)

Rotational-Raman spectra: ~4% energy scattered inelastically


Solar spectrum contains absorption lines
that get “filled in due to Raman scattering
For a given
incident
frequency ν
Sun
ν
Satellite
Rayleigh ν; Raman ν+/-Δν
scattering from
N2,O2
Retrieve cloud
pressure by
measuring reduction
in filling-in and
absorption
Absorption
from O2 -O2
Mie ν
Clouds screen
satellite observations
from scattering and
absorption below
Cloud
Earth’s surface
NASA

# Solar Fraunhofer Line Filling-in (Ring Effect) in the UV



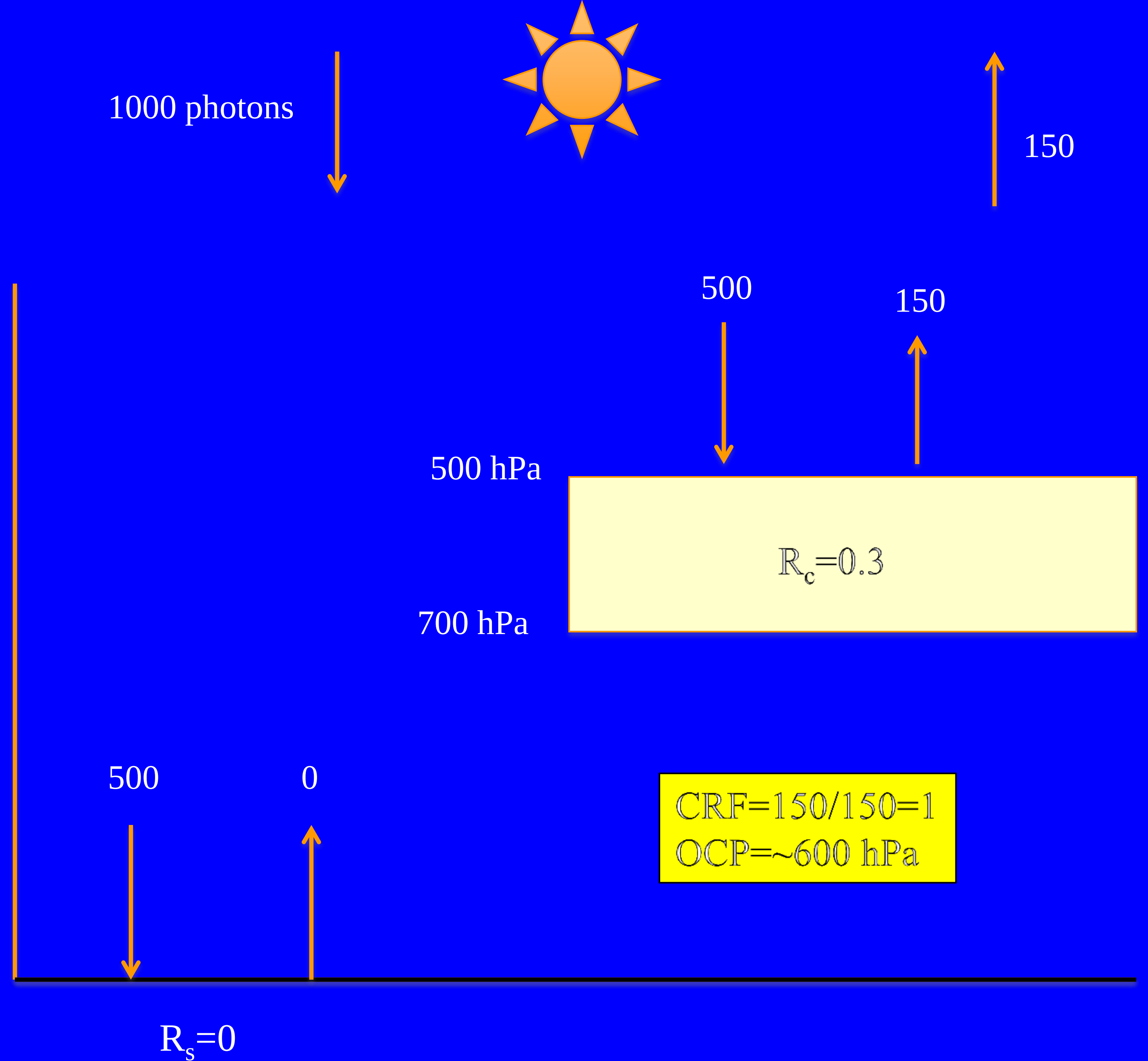

Raman scattering is additive: $I_{Raman} = I_{no\_Raman} + \delta$
Ring Effect is seen when one calculates $I/I_0$

# What is cloud radiance fraction (CRF)?

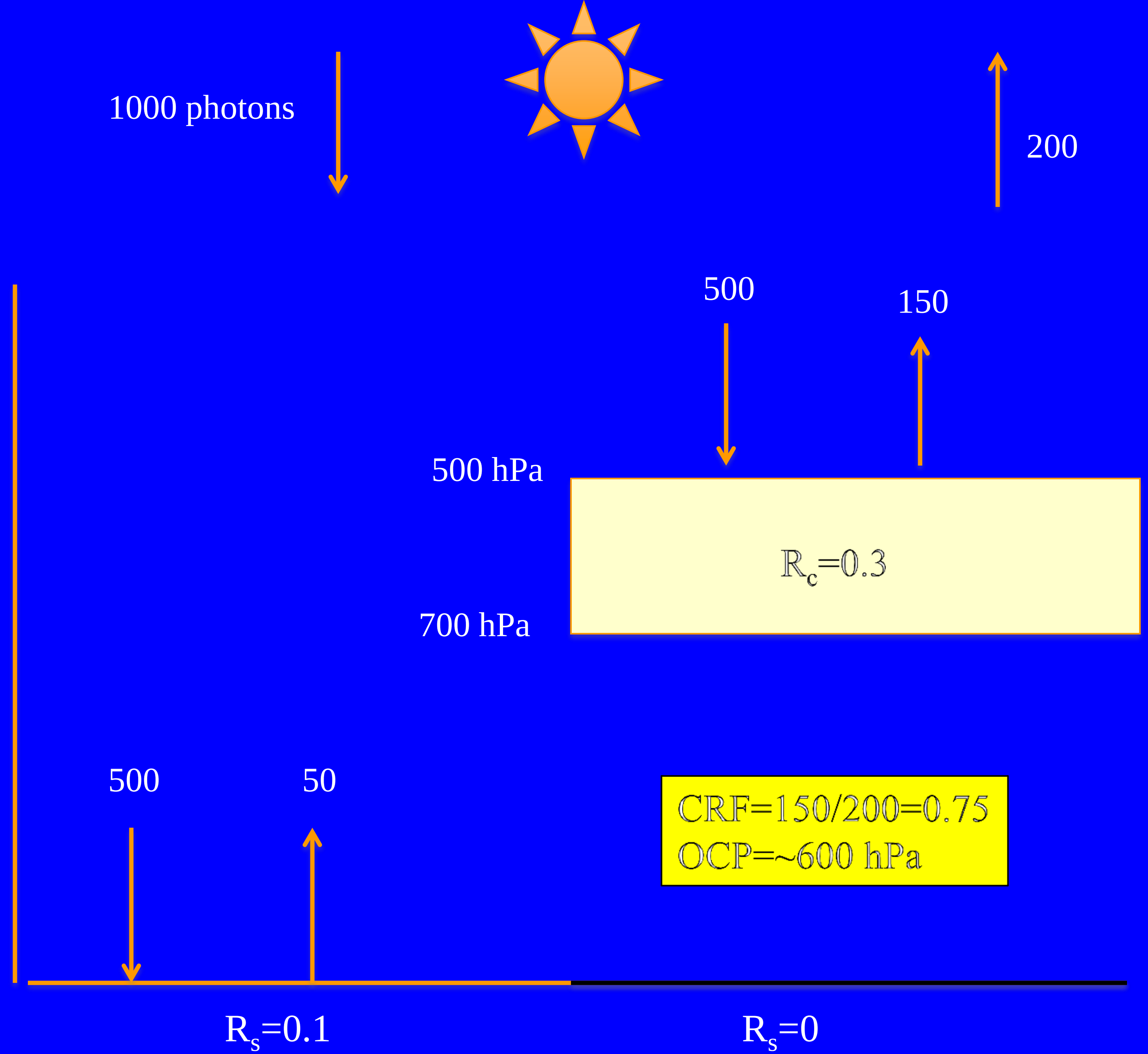
- It is the ratio of photons reflected by clouds/aerosols divided by total no of photons reaching the satellite.
- AMF of a trace gas is determined by CRF ($f_R$) and not by the area of a pixel covered by clouds (called geometrical cloud fraction, $f_g$).

$f_R \approx f_g I_c / I_m$, where $I_c$ is radiation from cloud and $I_m$ is the measured radiation

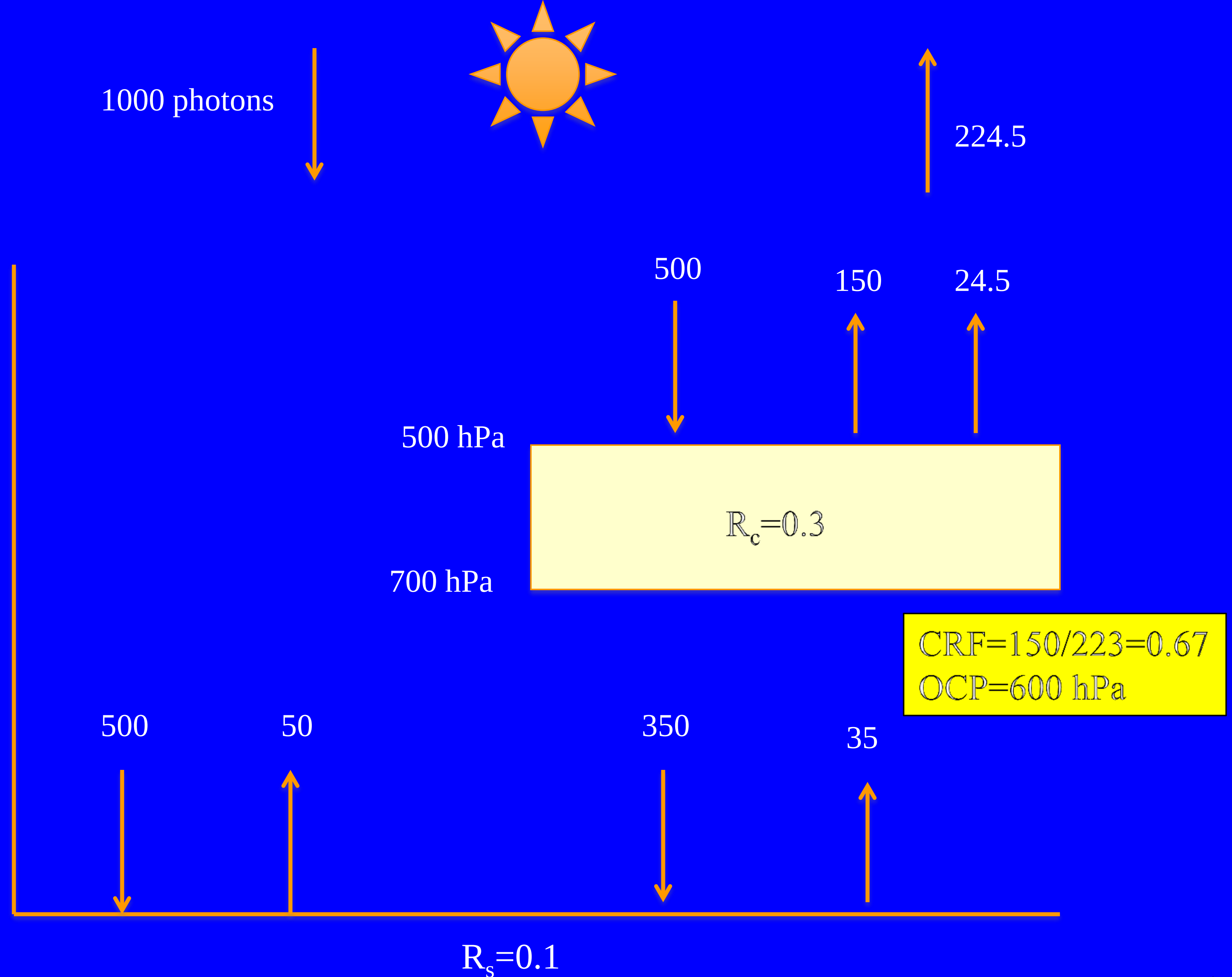
AMF= AMF_clear*(1-$f_R$)+ AMF_cloud*$f_R$




Case 1: Surface ref=0 cloud fraction= 50% no aerosol or Rayleigh

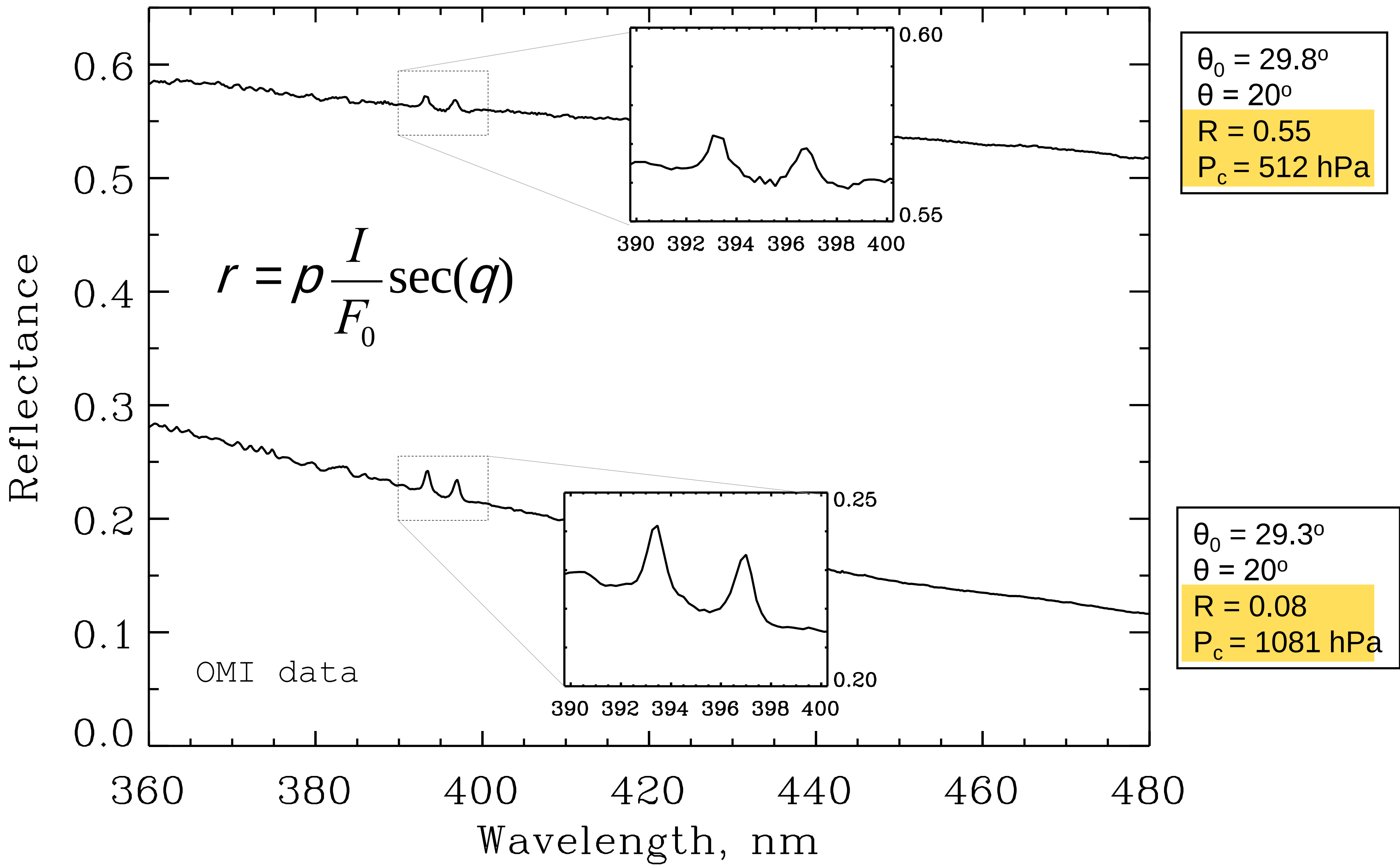



Case 2: Surface ref=0.1 cloud fraction= 50% Ignore radiation below the cloud

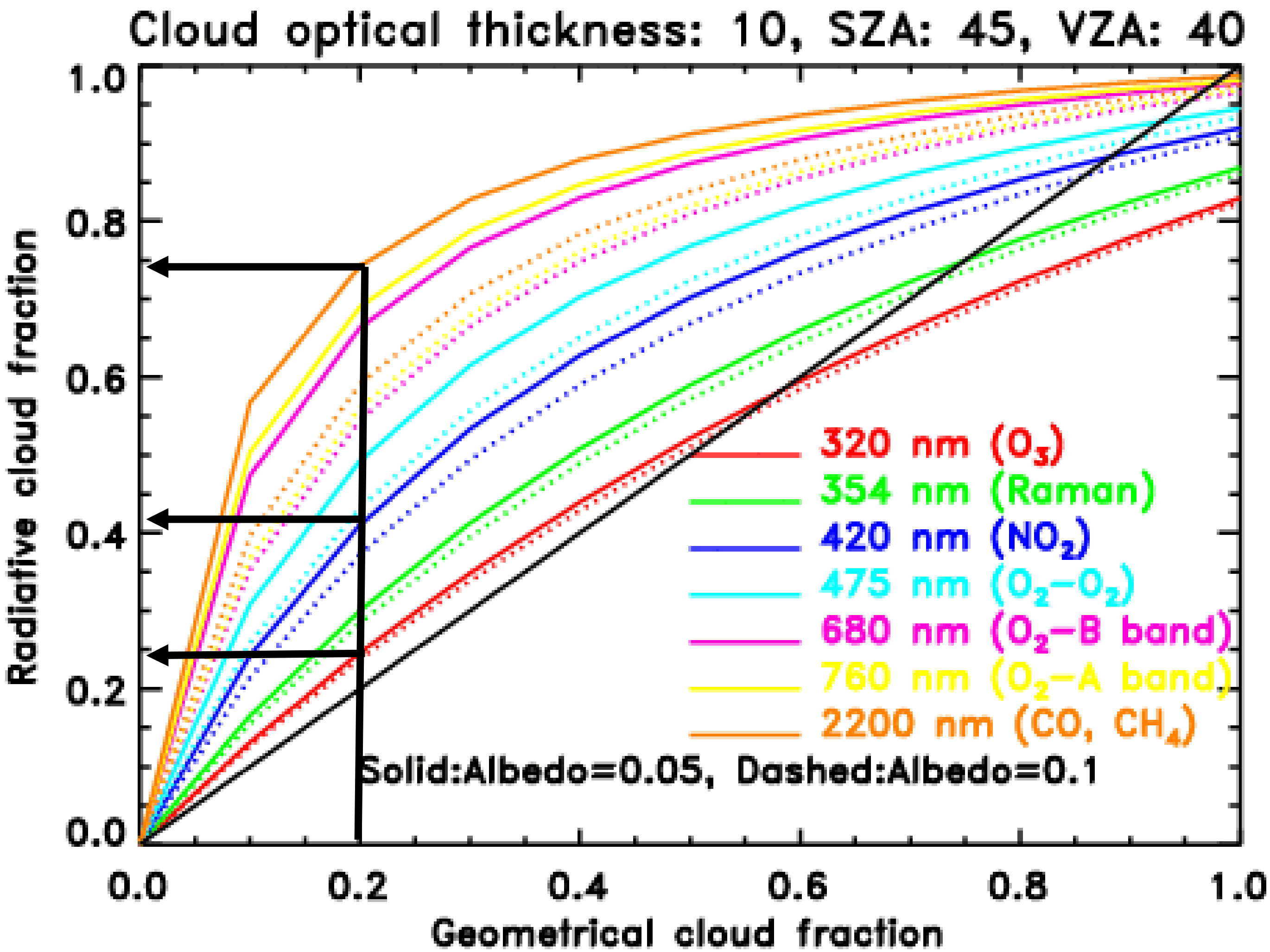



Case 3: Surface ref=0.1 cloud fraction= 50% Incl radiation from below cloud

# Effect of Rayleigh & Raman Scattering on UV/VIS spectra



# Rayleigh scattering effect on $f_R$




$f_R$ depends on $\lambda$, geom cloud fraction, cloud OT, and surface reflectance

# How well can we estimate AMF from the OCP/CRF concept?

- Should work well for convective clouds, since convection tends to vent the boundary layer and mix the gases.
- Works reasonably well if there are aerosols (with no mixed-in clouds).
- May not work well if there is thin cloud above a polluted boundary layer containing aerosols/fog, a common occurrence in Asia.

# Cloud Models

- Lambertian models
  - assume cloud are opaque Lambertian surfaces
- Plane-parallel models
  - assume clouds consist of thin sheet of particles extending to infinity in both X & Y direction
- Independent-pixel (IPA) approximation
  - assume photons from cloudy and clear part of the scene do not interact

# How do CRF from various models compare?

- It is far easier to determine CRF than the quantities that affect CRF individually.
- Opaque cloud models produce smaller CRF than those that treat clouds as transmitting
  - The former include radiation from below the cloud as part of the clear scene, while the latter include it as part of the cloudy scene.
  - However, all models appear to give similar AMF, though this still needs to be fully investigated for the GEMS observation geometry.

# Lambertian Models

- The simple LER model (SLER) assumes that surface/clouds/aerosols are at the same height

- The mixed LER model (MLER) assumes cloud and surface are at different heights. Aerosols are not explicitly considered.

# The SLER Model

For Lambertian Reflecting Surface:

$$I = I_0 + \frac{RT}{1 - RS_b}$$

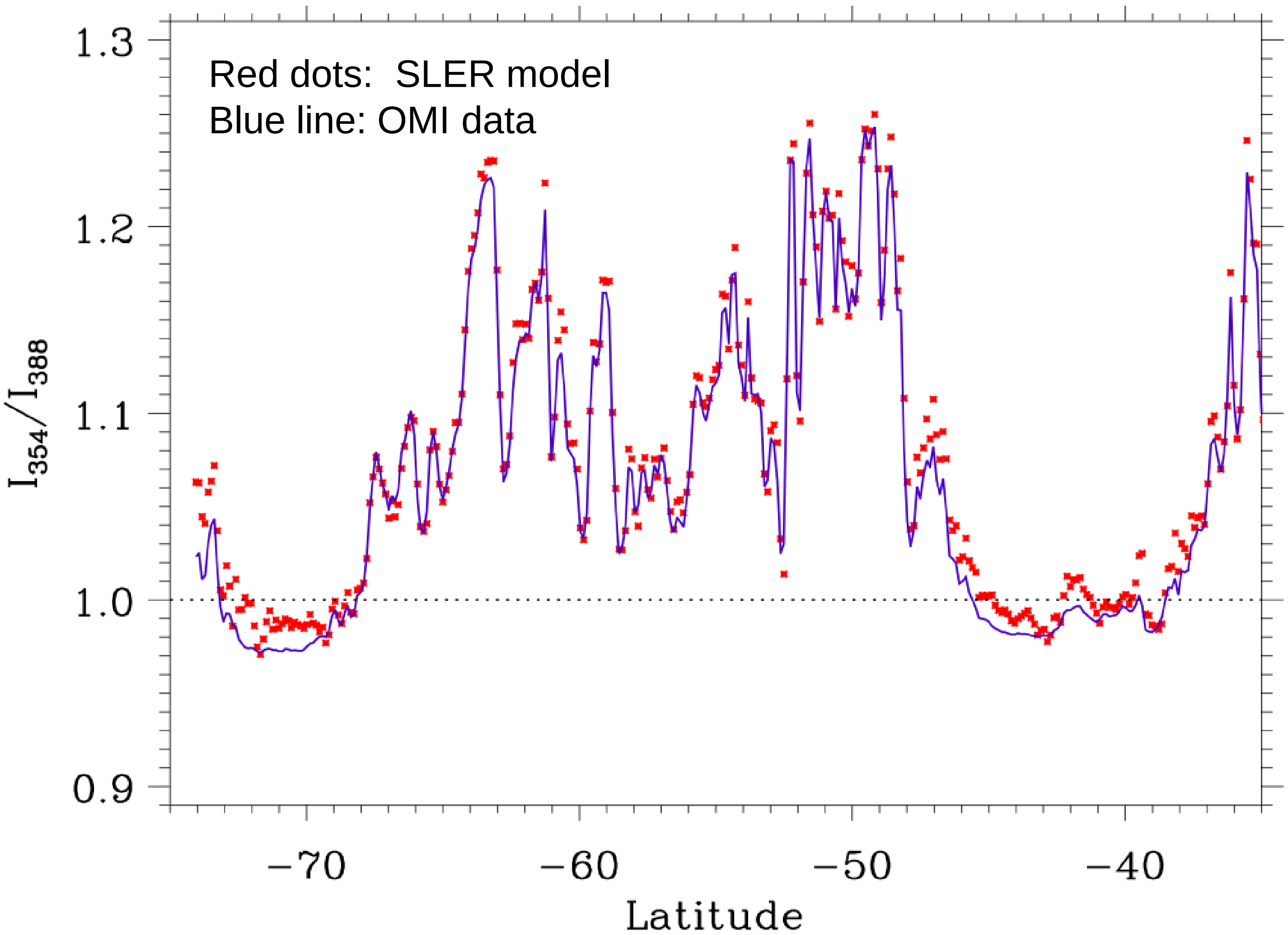
$$R = \frac{(I - I_0)}{T + S_b(I - I_0)}$$

- R is called Lambert-equivalent Reflectivity (LER)
- R and its spectral dependence can be calculated from radiances measured at wavelengths where the atmospheric absorption is small. For TOMS we use 340 and 380 nm.
- The method works best when one ignores cloud height, and assumes that clouds are at the surface. (See Ahmad et at., 2004)

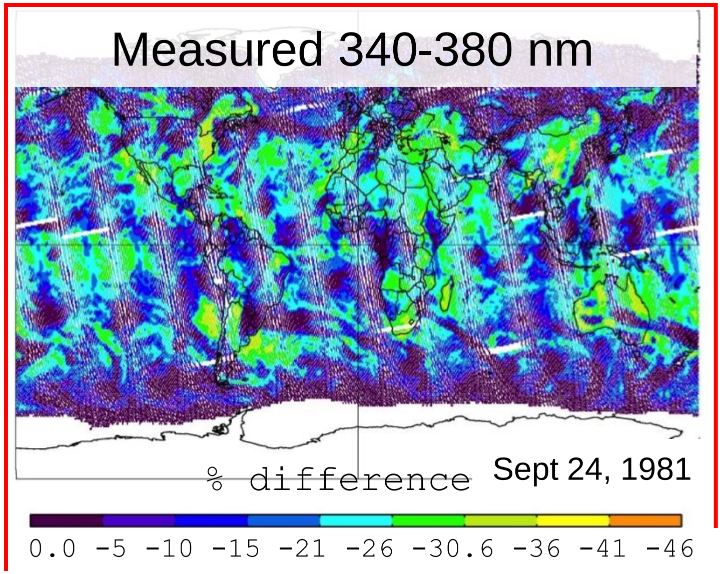
# Strengths of SLER model

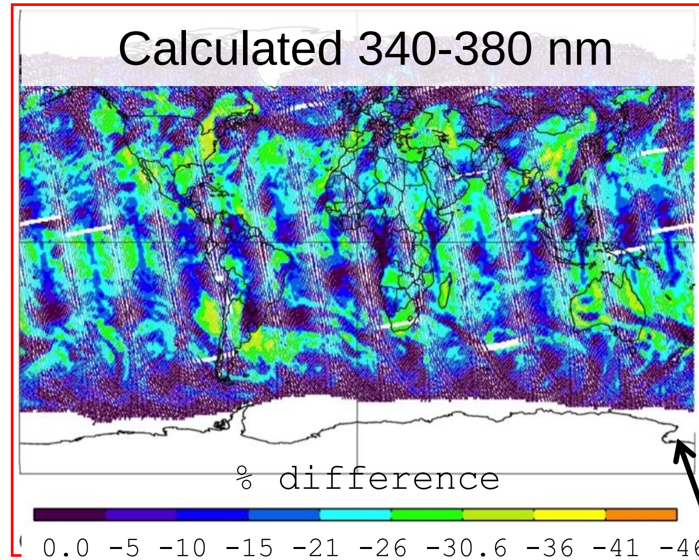
- Using just one parameter (R) it can model spectral dep of radiance due to Rayleigh scattering very well.
- An additional parameter (linear slope of R with $\lambda$) can account for aerosol absorption, terrain height, and non-Lambertian surfaces.
- Doesn't require knowledge of surface reflectivity, aerosols, cloud optical thickness, cloud fraction, cloud height or cloud type.

# How well does SLER work?

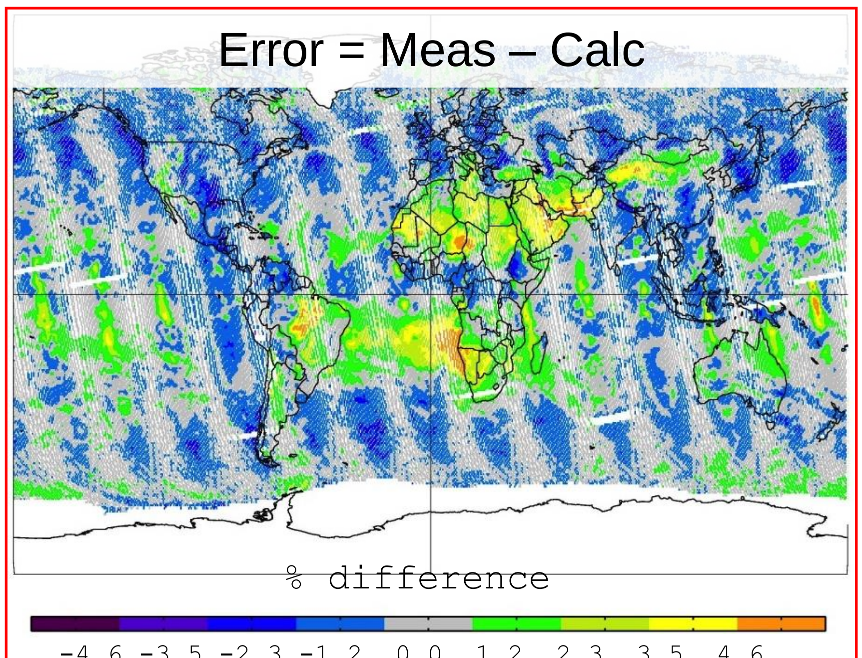


# Percent difference in radiances from TOMS using LER



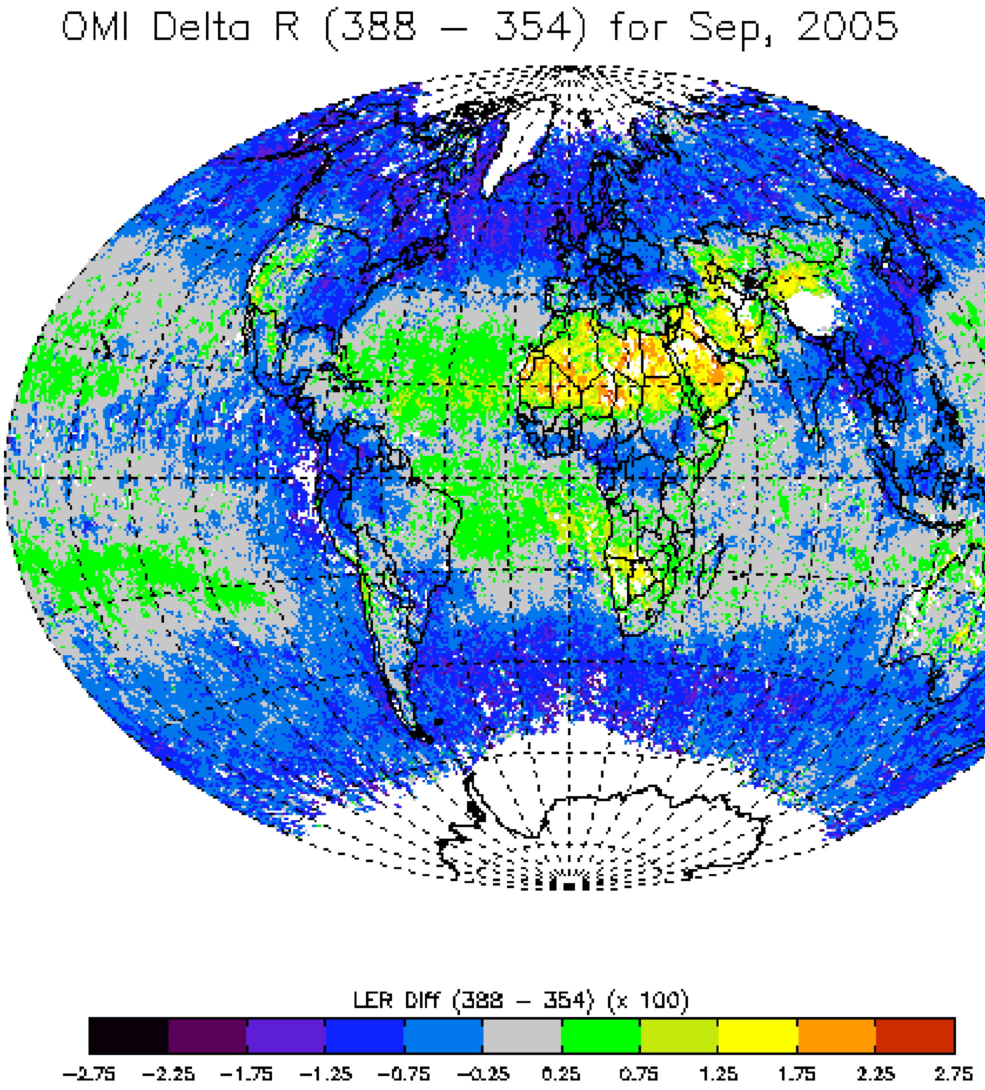




Pure LER model is used




Similar to AI

# R388-R354 from OMI Using SLER



# Estimation of CRF from LER

- Cloud reflectance $R_c \approx (R-R_s)/(1-R_s)$

  (ref: Krotkov et al., 1998)
- Calculate TOAR ($I_c$) assuming a Lambertian model with surface of reflectivity $R_c$ at OCP
- $f_R = I_c/I_m$

# The Mixed LER (MLER) model

$$I_{meas} = I_s(R_s, p_s)\left(1 - f_c\right) + f_c I_c^*(R_c = 0.8, p_c)$$

$$f_c = \frac{I_{meas} - I_s}{I_c^* - I_s}$$

- $f_c$ is called "effective" cloud fraction since the MLER model assumes $R_c$=0.8.
- $f_c$ is usually much smaller than the area covered by clouds, since most clouds have $R_c$<0.8.
- $f_R=f_c I^*_c/I_m$

# Other cloud models

- They require additional information that is very hard to get, e.g., cloud fraction, cloud vertical structure, and cloud type (water vs ice).
- There is no evidence that models that treat clouds as particles , e.g., the C1 model, work better than the two Lambertian models in explaining Rayleigh scattering, except for stratoform clouds.
- The primary value of these models is to assess the sensitivity of AMF to different assumptions about cloud properties.

# Summary

- AMF of trace gases in UV/VIS depends largely on CRF and OCP
  - Calculation of these quantities doesn't seem to depend on cloud model. The Lambertian models seem to work well.
- The primary issue is how to calculate the AMF of aerosol-cloud mixed scenes in polluted areas.
  - CRF cannot distinguish between cloud/aerosol, and the OCP assumption breaks down for such scenes.