AFRICAN DUST WORKSHOP

"Atmospheric Aerosols in the World and their Impact on the Caribbean"

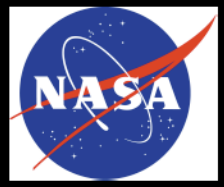
June 18 - Jun 25, 2011

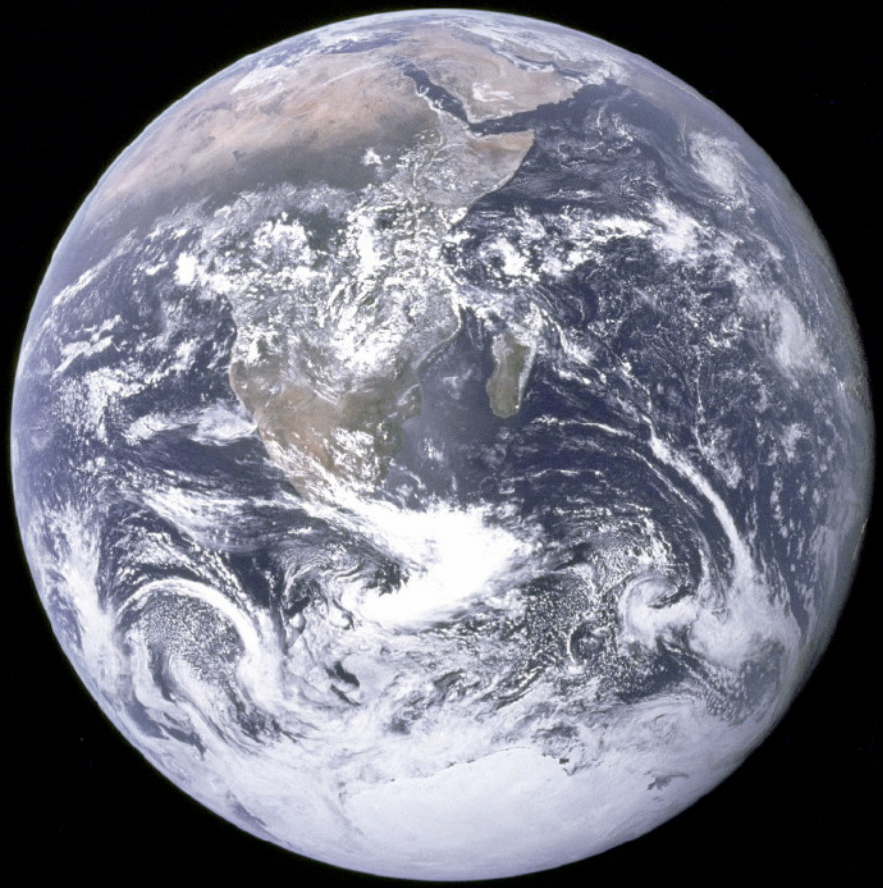
What is at the core of my work with: Clouds + Aerosols + Radiation, Remote Sensing & Climate?

Anthony B. Davis

Jet Propulsion Laboratory

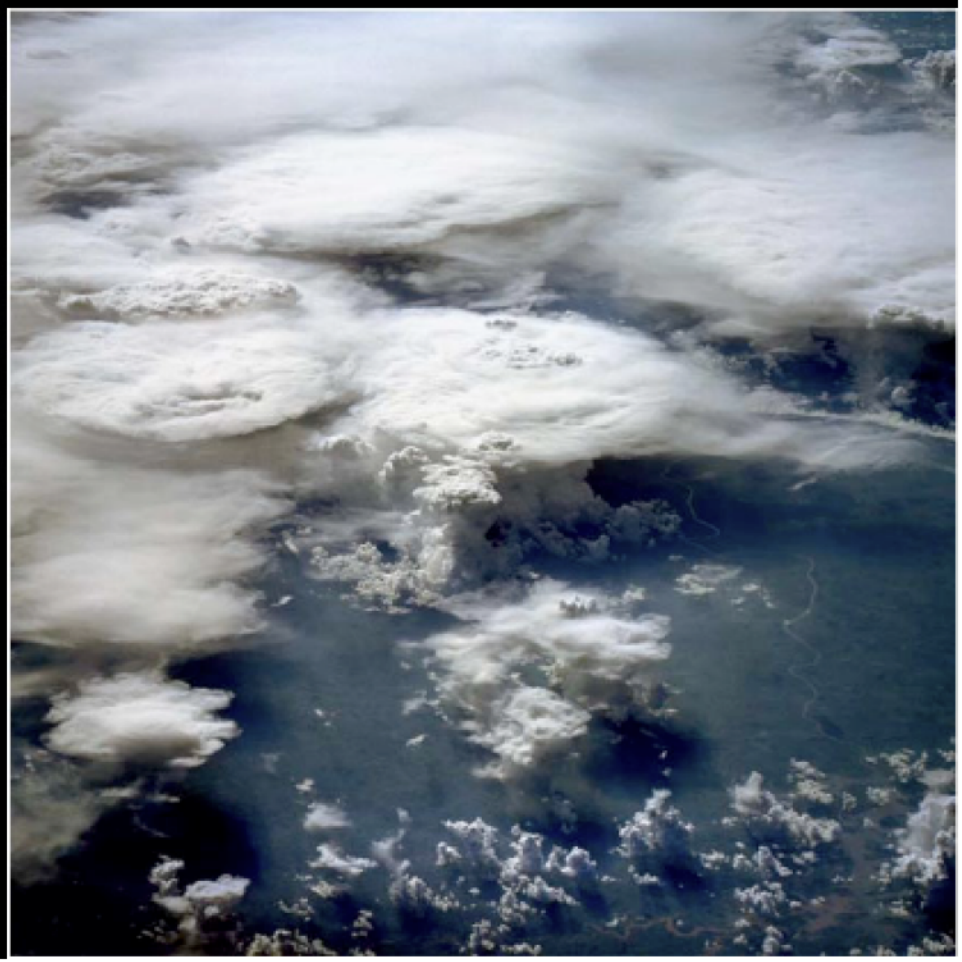
California Institute of Technology



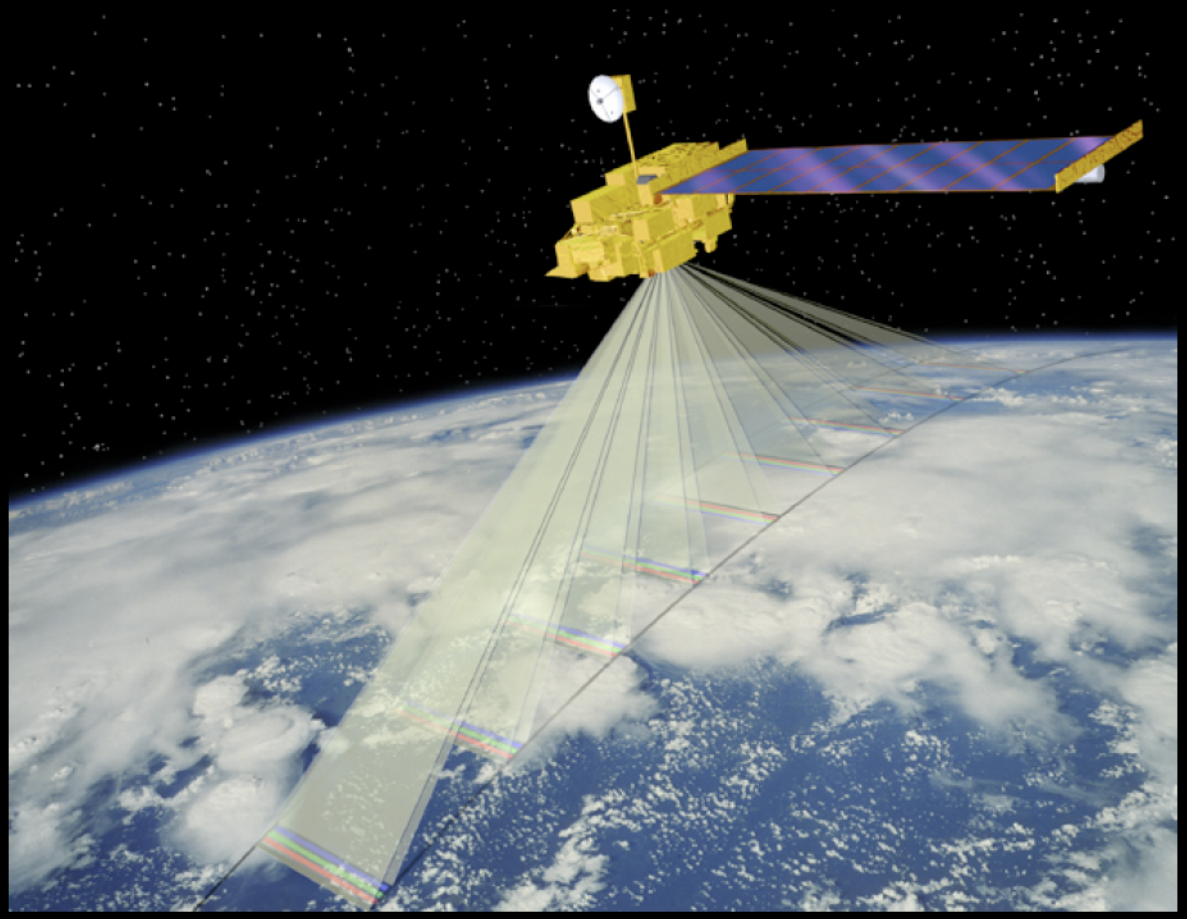


courtesy Space Shuttle astronauts ➔

← courtesy Apollo 17 astronauts



Multi-angle Imaging SpectroRadiometer (MISR)



Aboard the NASA Terra platform (polar orbiting, sun-synchronous, AM equator crossing time)

Nine view angles at Earth surface: 70.5° forward to 70.5° backward

Nine 14-bit pushbroom cameras

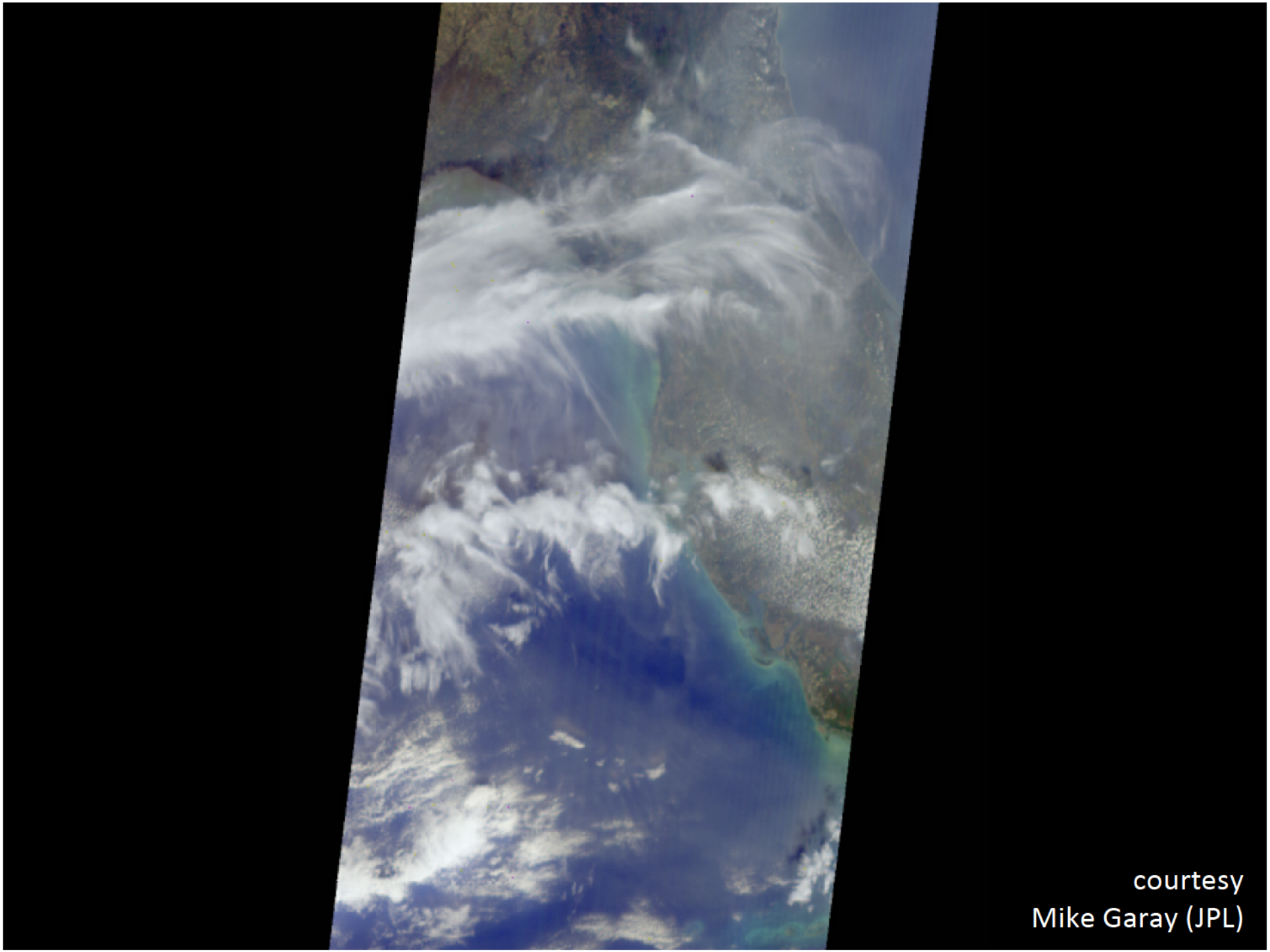
275 m - 1.1 km sampling

Four spectral bands at each angle: 446, 558, 672, 866 nm

400-km swath: 9-day coverage at equator, 2-day at poles

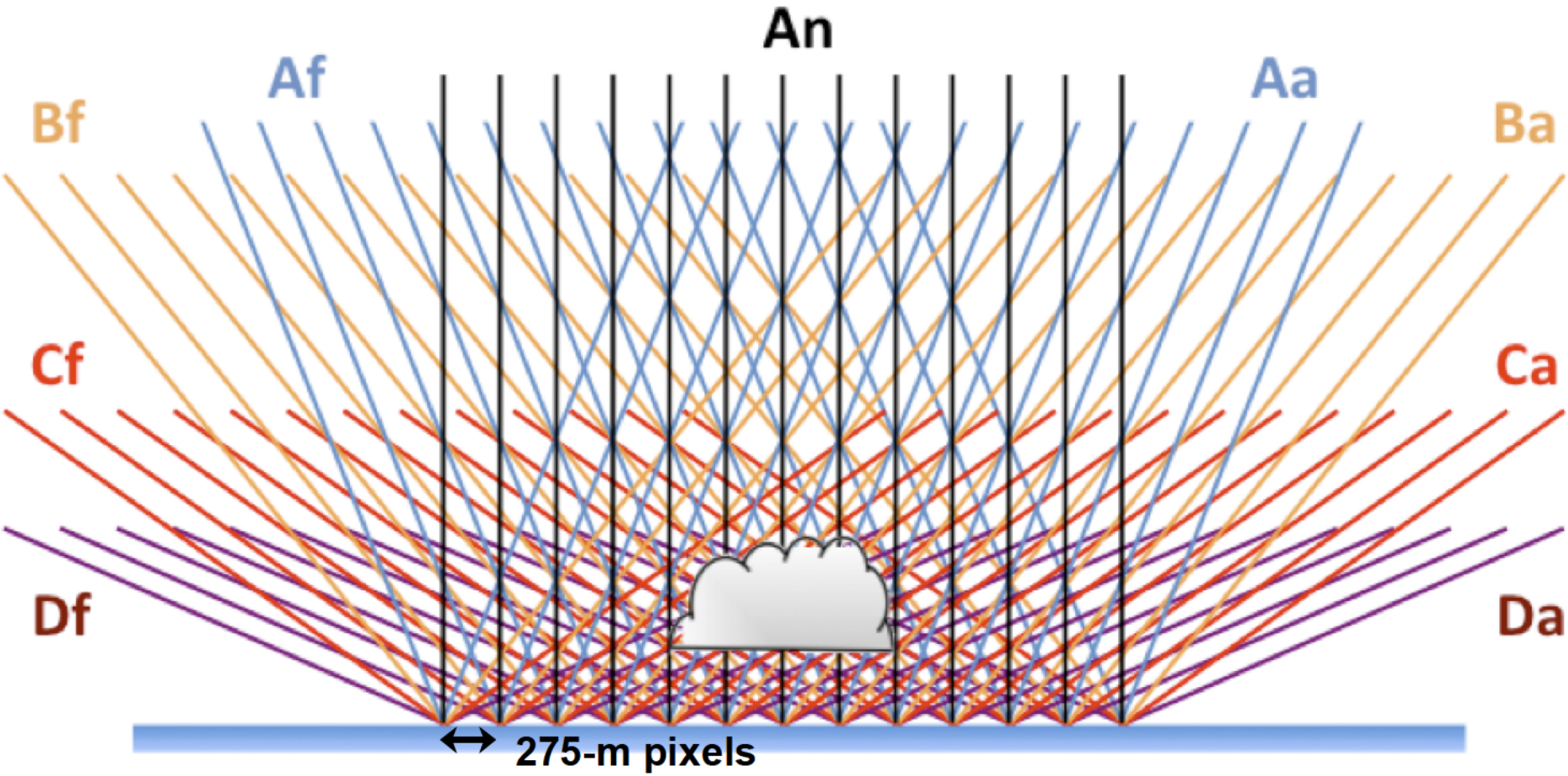
7 minutes to observe each scene at all nine angles

Jet Propulsion Laboratory, California Institute of Technology


courtesy
Mike Garay (JPL)

MISR
Multi-angle Imaging SpectroRadiometer

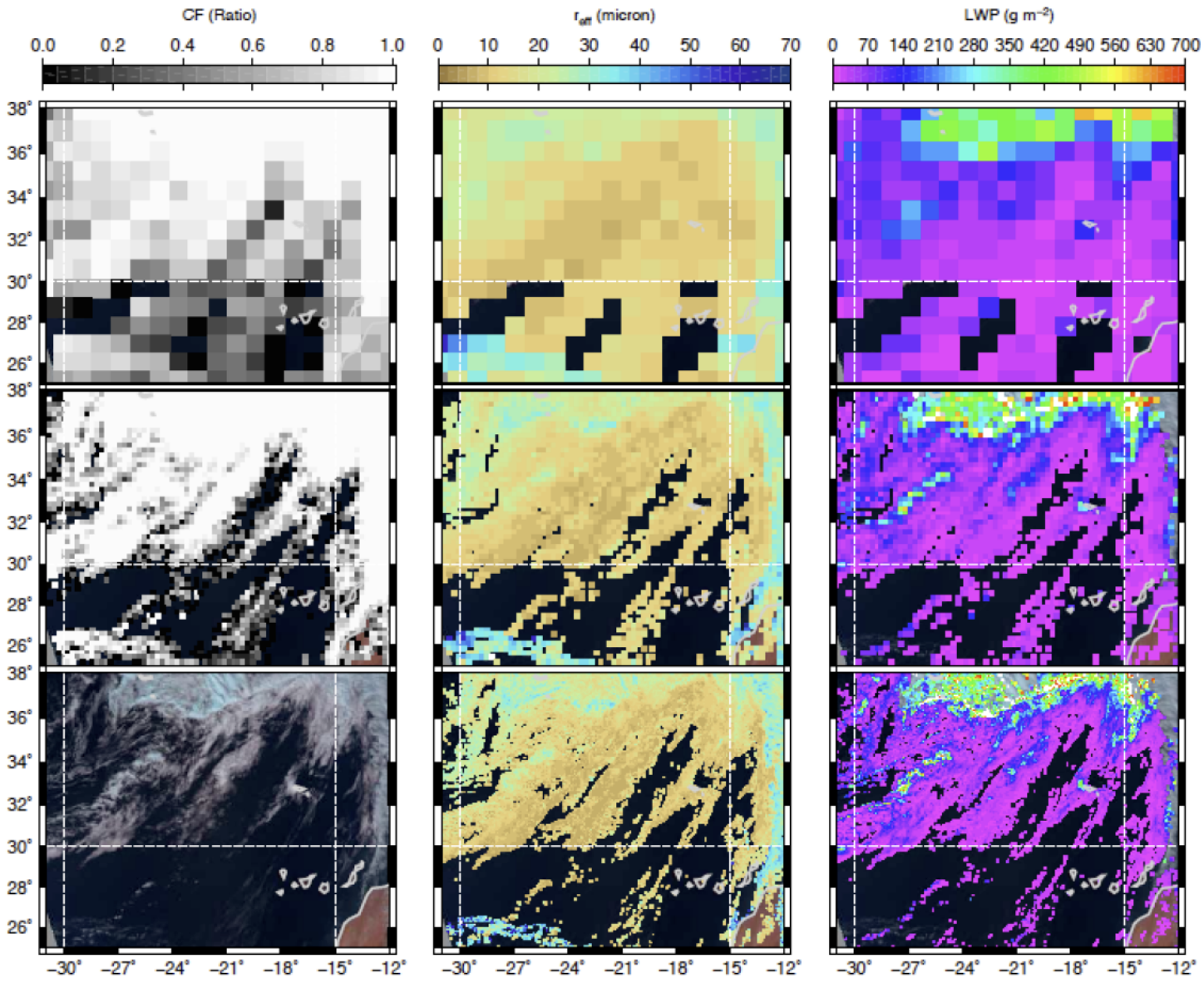
Definition of cloud-mask volume using MISR's nine push-broom cameras



Radiances & Products

- So far you've only seen **"Level 1"** data:
  - raw measurements by imaging instruments, a.k.a. radiances
- Earth scientists of every ilk actually want geophysically meaningful quantities!
- Need to translate radiances into temperatures, densities, profiles thereof, surface properties, aerosol properties, cloud properties, etc., etc., etc. (a very long list!)
  - **"Level 2"** data
  - ideally on a pixel-by-pixel basis
- Calls for *predictive physics-based model for the radiances, given a model for the scene:* "Radiative Transfer" (RT)
- Then calls for an "inversion method" for inferring scene properties from radiances (get RT input from its output)

MODerate resolution Imaging Spectrometer (MODIS): 0.25+ km pixels, processed, aggregated



coarser scales (toward where climate models work)

Radiative Transfer 101

- **Three core problems:**
  - **Propagation**
  - **Scattering**
  - **"Repeat" (multiple scattering)**

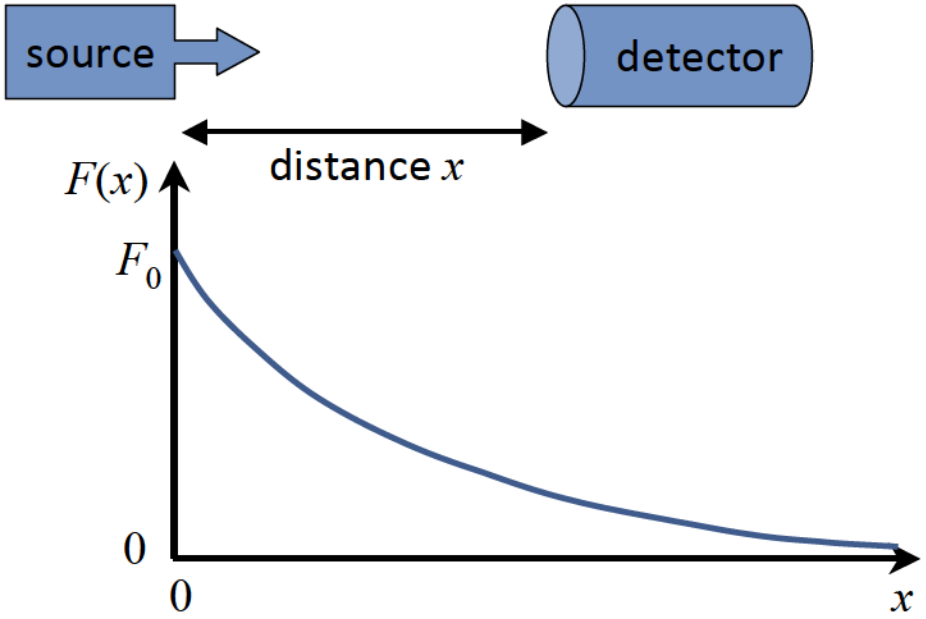
Note: The following slides contain more complete material than presented at the lectern. More specifics are provided, for the interested readers.

Radiative Transfer 101

- **Propagation problem: get light from A to B**

Radiative Transfer 101

- **<u>Propagation problem:</u> get light from A to B**
  - One single optical property to define



Radiative Transfer 101

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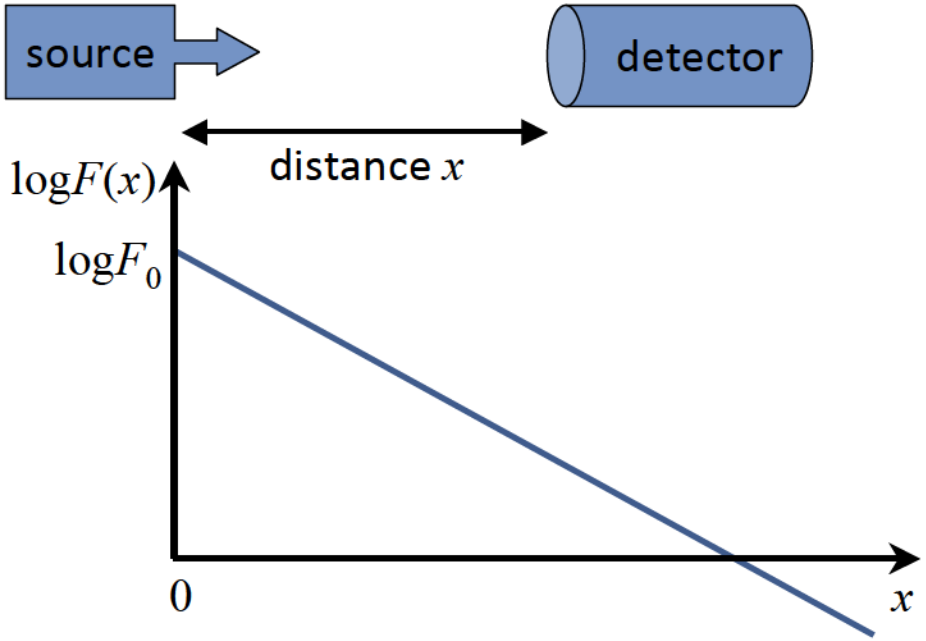

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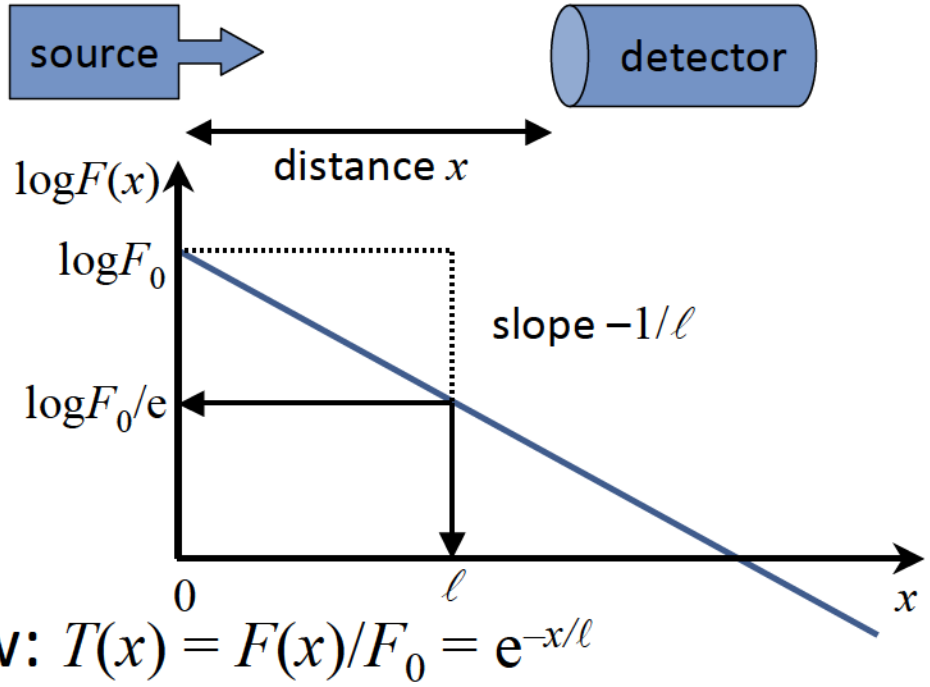

$$\frac{1}{\mathrm{e}} = 0.36788\cdots$$

  - Beer's law: $T(x) = F(x)/F_0 = \mathrm{e}^{-x/\ell}$
  - ℓ is the "e-folding distance" of the light of interest

Radiative Transfer 101

- **<u>Propagation problem:</u> get light from A to B**
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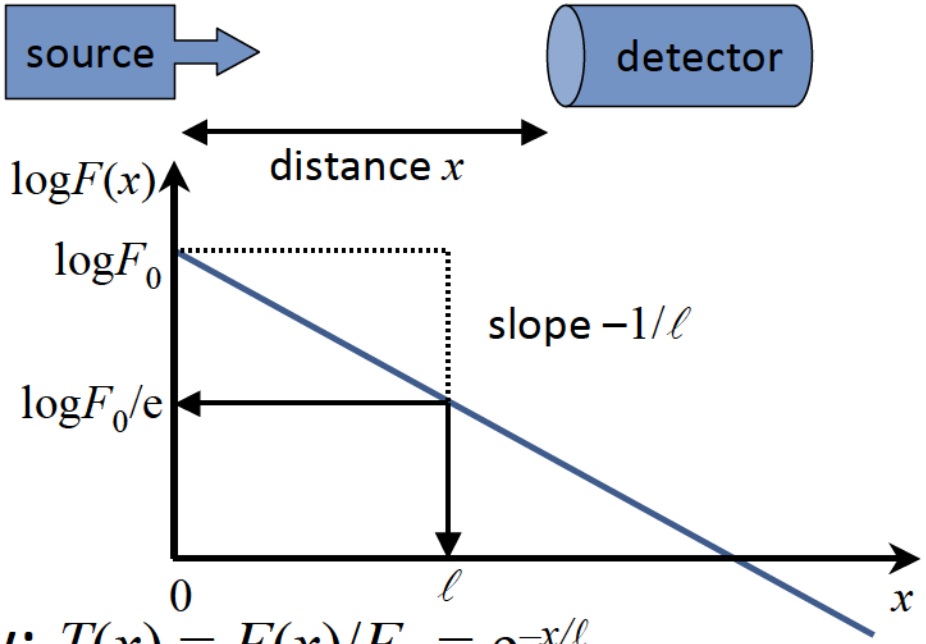


$$\frac{1}{\mathrm{e}} = 0.36788\cdots$$

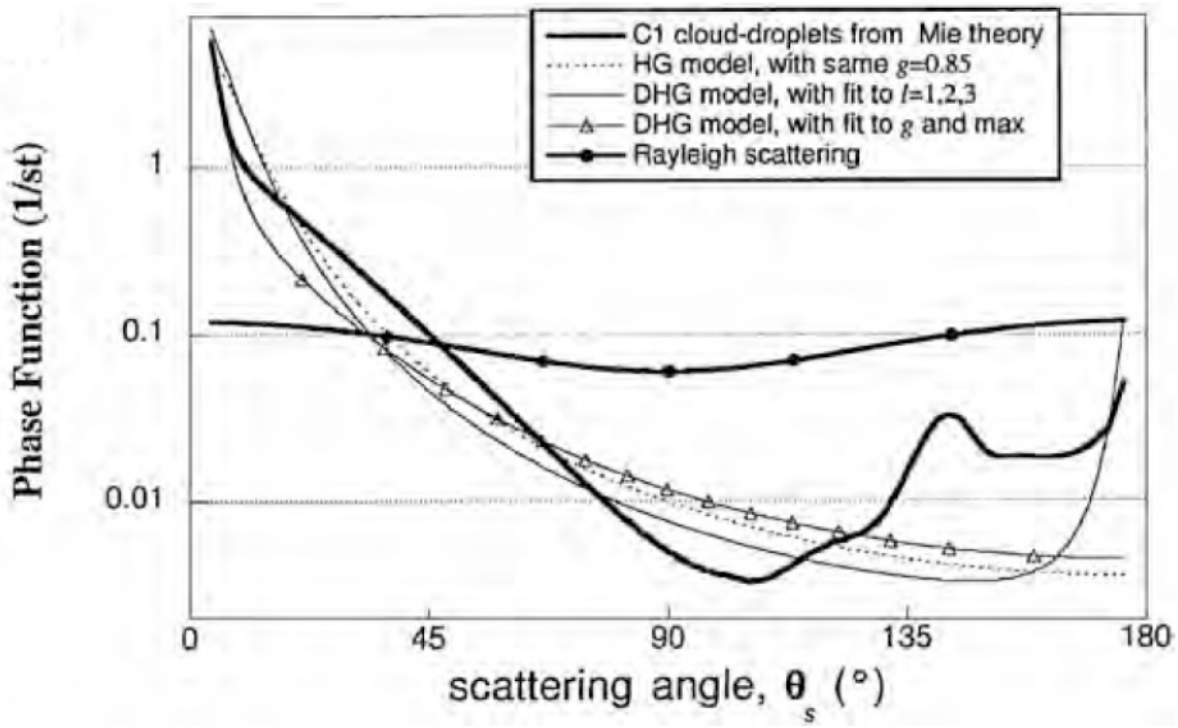
  - Beer's law: $T(x) = F(x)/F_0 = \mathrm{e}^{-x/\ell}$
  - AeroNet inverts this to infer "aerosol optical depth"
    AOD $= x/\ell$ where x is the thickness of the aerosol layer

Radiative Transfer 101

- **Scattering problem: get light from one direction (A to B) into another direction (B to ?)**

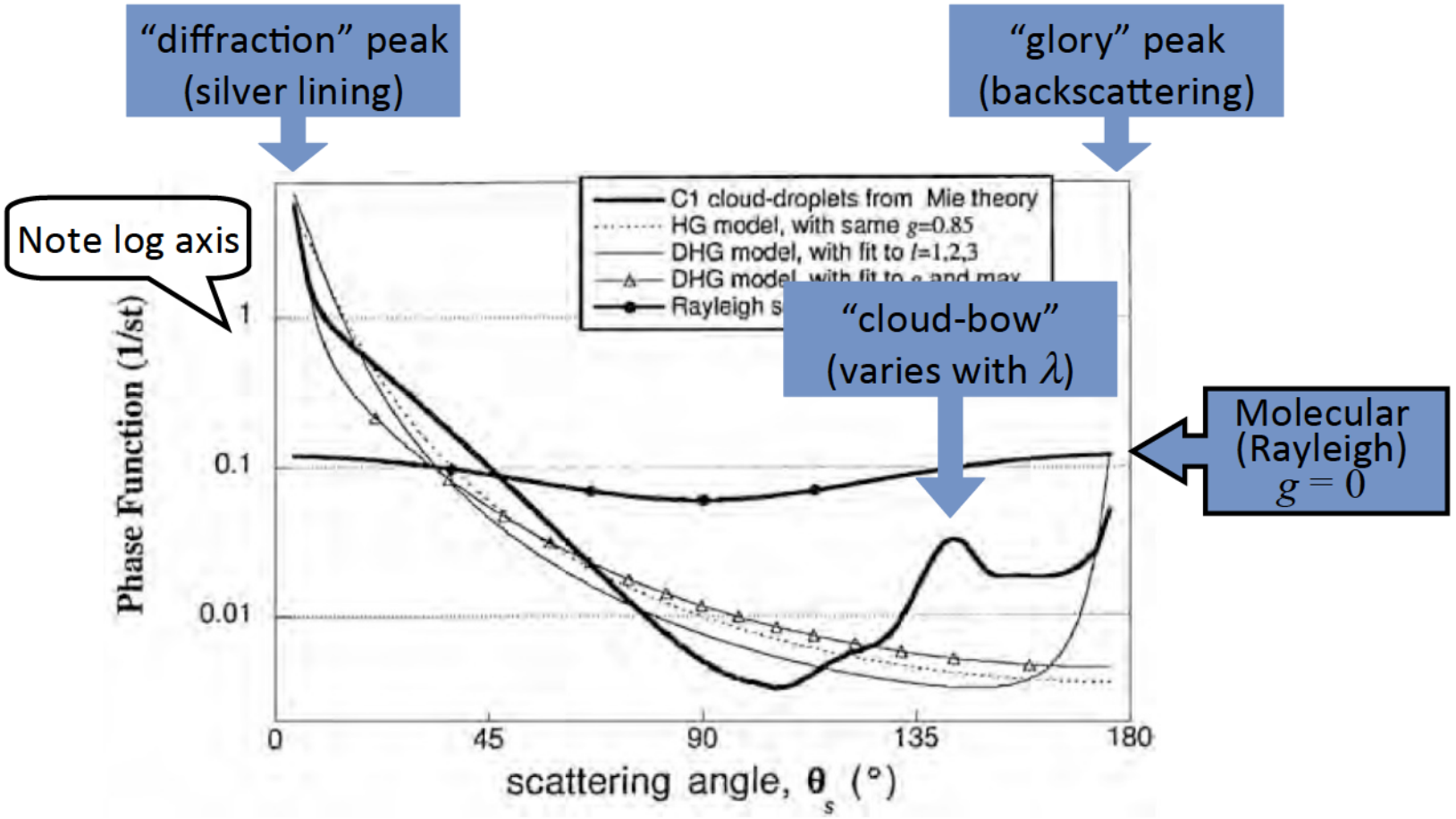
Radiative Transfer 101

- **<u>Scattering problem:</u> get light from one direction (A to B) into another direction (B to ?)**
  - *new concept:* "phase function," which describes how much light scatters into all possible directions



Radiative Transfer 101

- **<u>Scattering problem:</u> get light from one direction (A to B) into another direction (B to ?)**

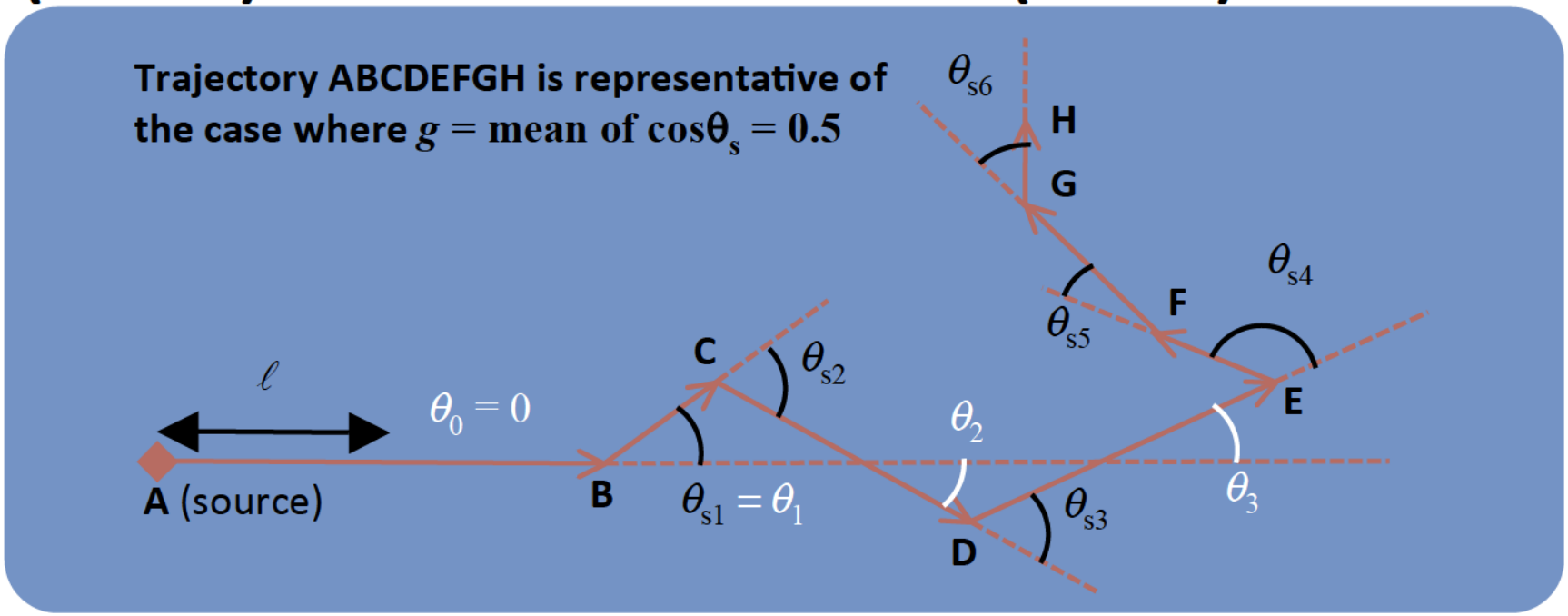


Radiative Transfer 101

- **<u>Scattering problem:</u> get light from one direction (A to B) into another direction (B to ?)**
  - Rayleigh scattering by molecular atmosphere
    - blue sky phenomenon
  - Scattering by atmospheric particles, assumed spherical
    - some natural and pollution sources of aerosol
    - cloud droplets
  - Scattering by atmospheric particles, *not* assumed spherical
    - other natural and pollution sources of aerosol
    - ice cloud crystals (sun dogs, etc.)
  - **Memory of previous direction, and loss thereof**
    - **mean cosine of scattering angle ("asymmetry factor," g)**
    - **iterated scattering**

Radiative Transfer 101

- **Scattering problem:** get light from one direction (A to B) into another direction (B to ?)



  - Memory of previous direction, and loss thereof
    - mean cosine of scattering angle ("asymmetry factor," g)
    - iterated scattering

Radiative Transfer 101

- **<u>Scattering problem:</u> get light from one direction (A to B) into another direction (B to ?)**

If $< \cos\theta_{sn} > = g$ $(n = 1,2,\ldots)$, where <X> means "mean of X," then what is $< \cos\theta_n >$?

(where $\theta_0 = 0$ and $\theta_n = \theta_{s1} + \theta_{s2} + \theta_{s3} + \ldots + \theta_{sn}$)

Answer (in the absence of absorption): $< \cos\theta_n > \; = g^n$

How many scatters (n^*) before $< \cos\theta_n > \; \ll \; < \cos\theta_n > = 1$, when g is ≈ 1?

Answer (loss of directional memory): $n > n^* \approx \dfrac{1}{1-g}$

How far (ℓ_t) did the light propagate (on average) before that happened?

Answer: $\ell_t \approx \dfrac{\ell}{1-g}$

  - **Memory of previous direction, and loss thereof**
    - **mean cosine of scattering angle ("asymmetry factor," g)**
    - **iterated scattering**

Radiative Transfer 101

- **Repeat [propagation & scattering] until …**
  - Absorption (by molecules, particles, or surface), or …
  - Escape (to space), including …
  - Detection (actually a sampling of the radiance field)
- **This defines the multiple scattering problem**
- **a.k.a. diffuse reflection/transmission problem**

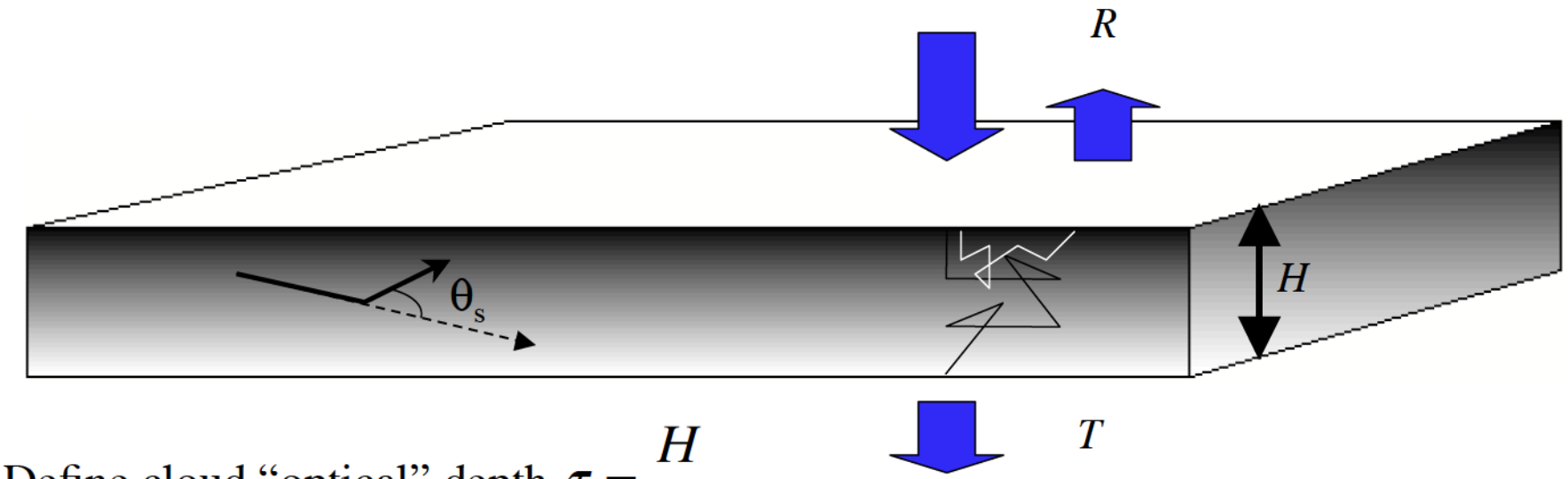
Radiative Transfer 101

- **Diffuse reflection/transmission problem:**

Is this a cloud?

Yes, it is! … because we can solve its forward (and inverse) RT problems

Assume no absorption, hence
R(eflectance) + *T*(ransmittance) = 1



Define cloud "optical" depth $\tau = \frac{H}{\ell}$

$$\frac{R}{T} \approx \frac{(1-g)\tau}{2\chi} \qquad \begin{cases} g = \langle \cos\theta_s \rangle \approx 0.85 \\ \chi \approx 2/3 \end{cases}$$

Yes, it is! … because we can solve its forward (and inverse) RT problems

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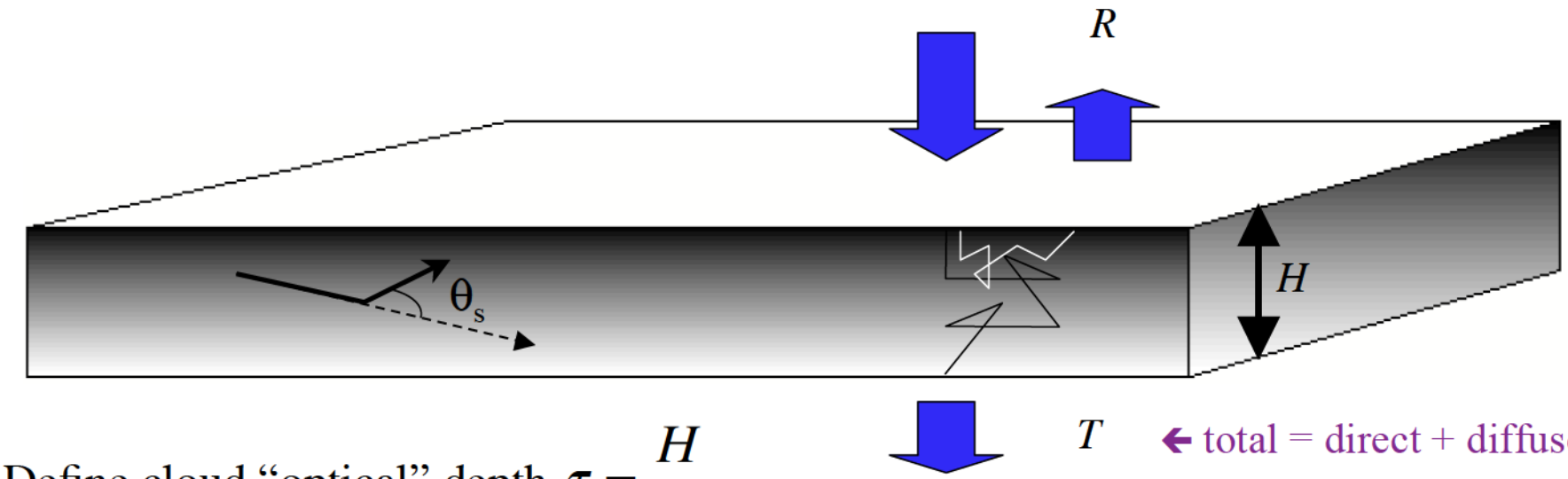

← total = direct + diffuse

Define cloud "optical" depth $\tau = \frac{H}{\ell}$

Recall Beer's law:

$T_{direct} = e^{-\tau}$ (here $<< T \leq 1$)

Here, by contrast:

$T \propto 1/\tau$ (when $\tau >> 1$)

$$\frac{R}{T} \approx \frac{(1-g)\tau}{2\chi}$$

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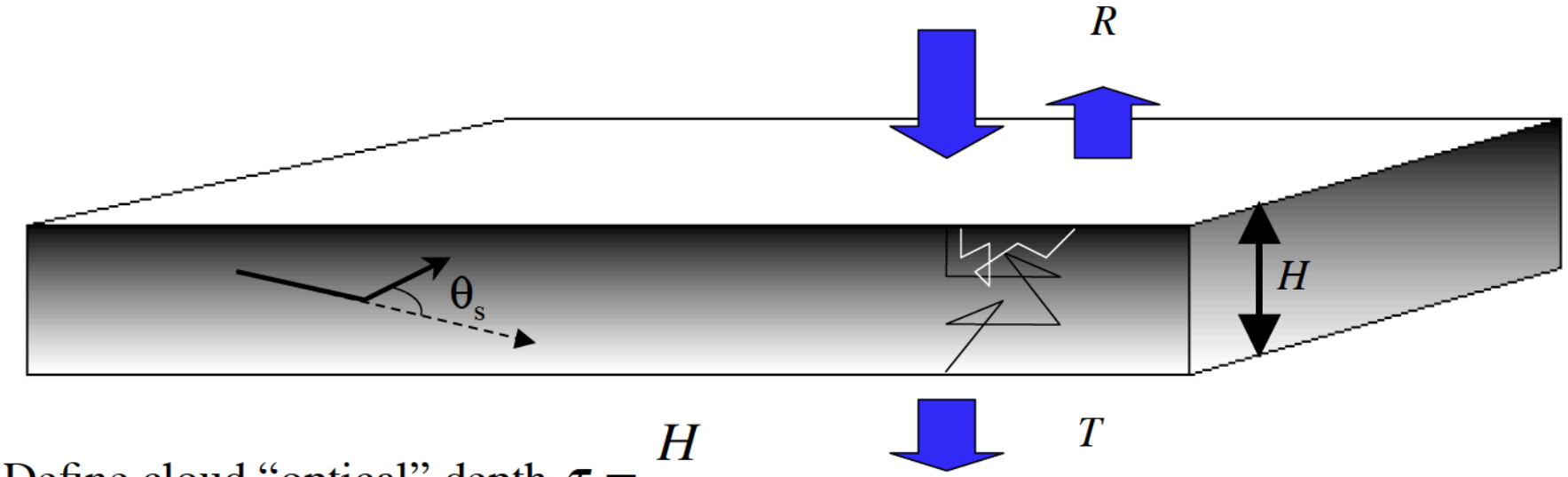

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$$\frac{R}{T} \overset{?}{\approx} \frac{(1-g)\tau}{2\chi} \quad \checkmark$$

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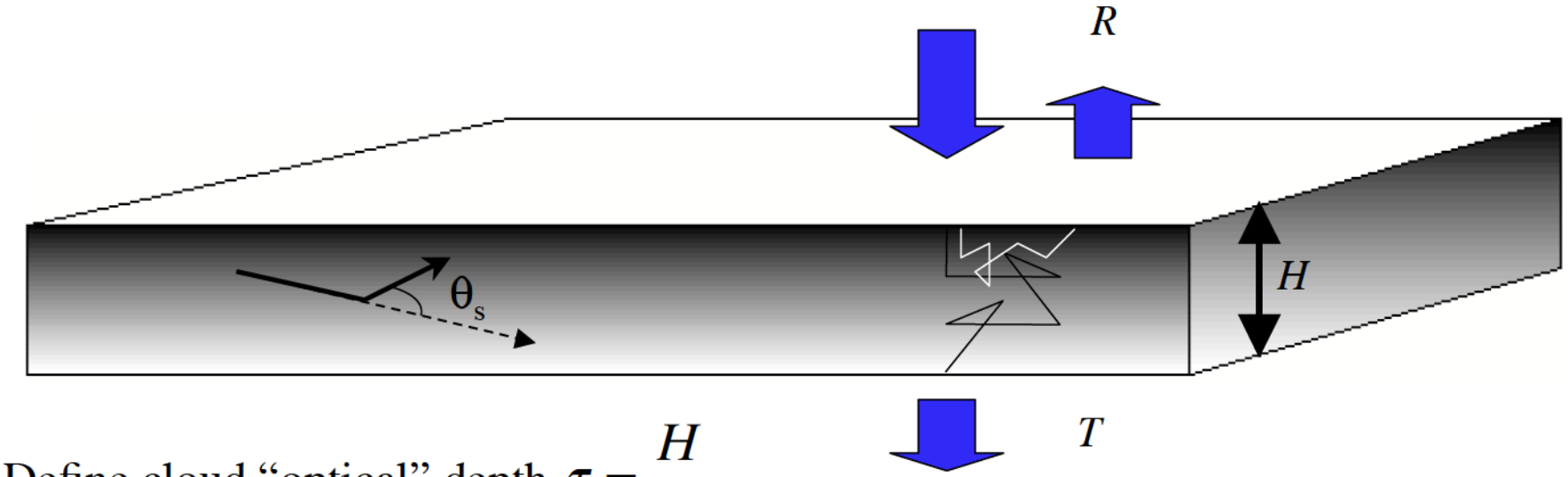

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✔ ?

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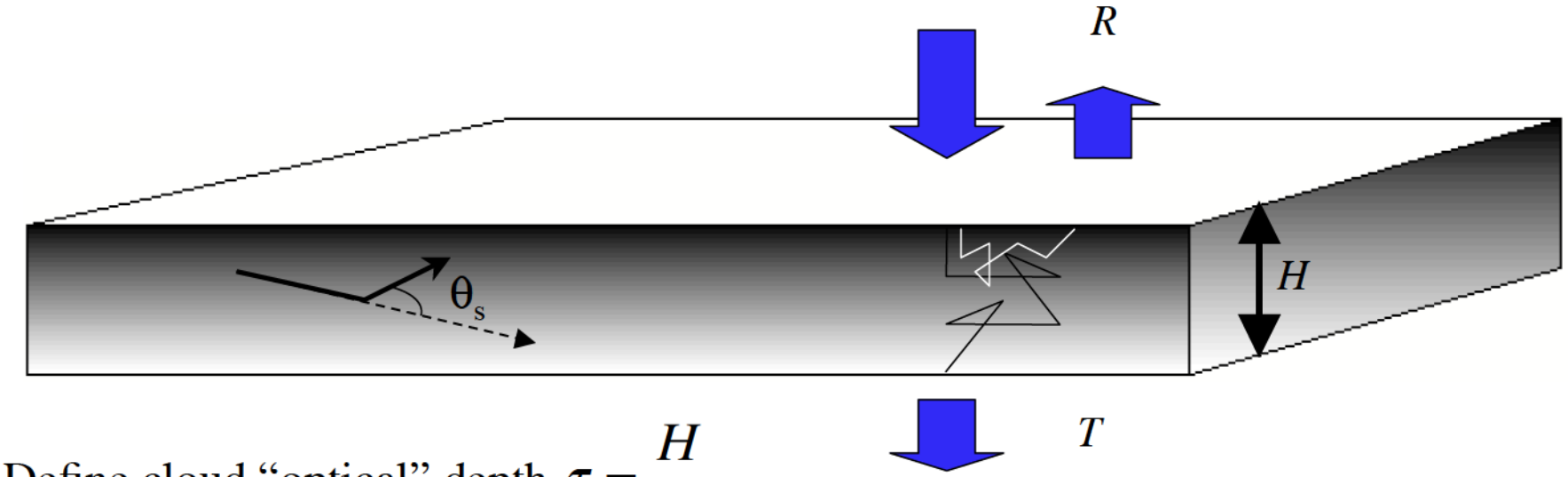

Define cloud "optical" depth $\tau = \frac{H}{\ell}$

?

$$\tau \approx \left(\frac{2\chi}{1-g} \right) \times \frac{R}{T}$$

✔

$$\begin{cases} g = \langle \cos\theta_s \rangle \approx 0.85 \\ \chi \approx 2/3 \end{cases}$$

My goals for the workshop:

- Give a taste for what's "under the hood" in atmospheric remote sensing … and maybe a healthy dose of skepticism about "Level 2" products
- Meet in small groups
- Figure out …
  - Propagation problem
  - Scattering problem (especially, directional memory loss)
  - Diffuse transmission/reflection problem
- There are several simple and insightful derivations for each expression (applicable to STEM curriculum?)
- Connect all of the above with classical optics, as it is presented in the classroom

Off-Beam Cloud Lidar:

A Milk-Based Demo

(for steady-state/CW source)

How much milk?

What to observe?

Radiative transfer regime?

Atmospheric analog?

clean H_2O, no milk	2-3 drops	many drops	enough	4 times more
"ground" return	+ beam return	+ volume return	"spot" fills free surface	"spot" shrinks by a factor of 2
no scattering	single scattering	low orders of scattering	high orders of scattering	higher orders of scattering
no atmosphere	clear atmosphere	hazy atmosphere	cloud	denser cloud

My research statement:

- Go beyond the standard (horizontally uniform and infinite slab) model that defines “1D” RT
- Use 3D RT:
  - Account to unresolved (sub-pixel) spatial variability
  - Account for resolved spatial variability (cross-pixel fluxes)
- Also, use time-dependent 1D and 3D RT:
  - Pulsed laser sources (lidar, but with multiple scattering)
  - Equivalence between transfer time and absorption by a uniform gas (prime candidate is oxygen)

Thank you!

Questions?

Acknowledgments:

support from NASA/ESD, DOE/OSc & -/NNSA

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