A Necessary Step Toward Cloud Tomography from Space using MISR and MODIS:
Understanding the Physics of Opaque 3D Cloud Image Formation

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**Do *these* clouds look like →
horizontally infinite plane-parallel slabs?**

Too bad! That is indeed the assumption in *operational* passive cloud remote sensing in the solar spectrum. **That said,** there are good reasons to continue to use the ensuing bi-spectral (Nakajima & King, 1990) algorithm based on 1D radiative transfer (RT):

- *something* has to be done about every cloudy pixel, and they are produced at such a rate that *it* has to be really simple;
- some important cloud types (eg, marine strato-cumulus) are *reasonably well approximated*;
- even if the retrievals are often biased, per DS17, we need to maintain a *program-of-record*.

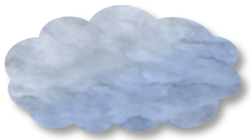
That said, we will *reinvent* VNIR+SWIR cloud remote sensing for 3D convective clouds based on …

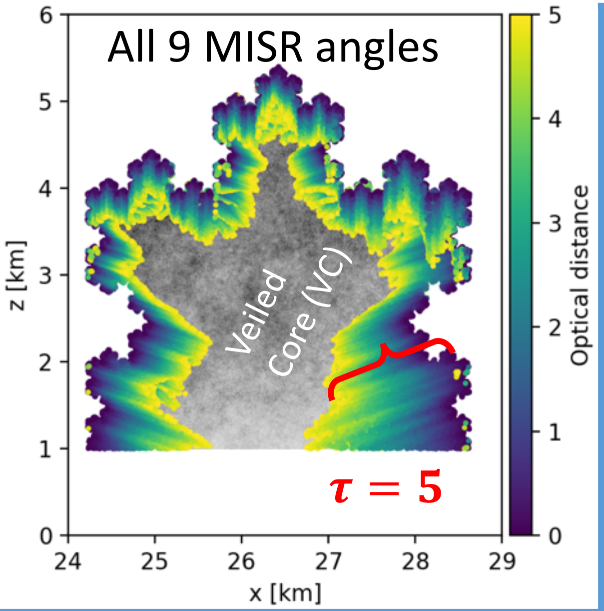
… physical insights into cloud image formation.

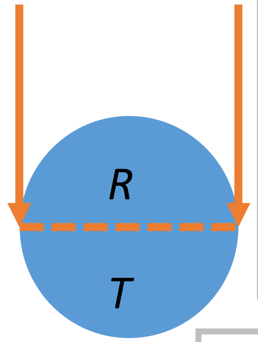
Namely, that cloud imagery is shaped by 2 complementary diffusion processes:

Diffusion process #1 & #2 [#1 & #3]

- random walks unfold on 2D sphere (*direction* space)
- in the *outer shell* (cloud\VC)
- gradual loss of *directional* memory
- shapes pixel-scale *"features"* in images







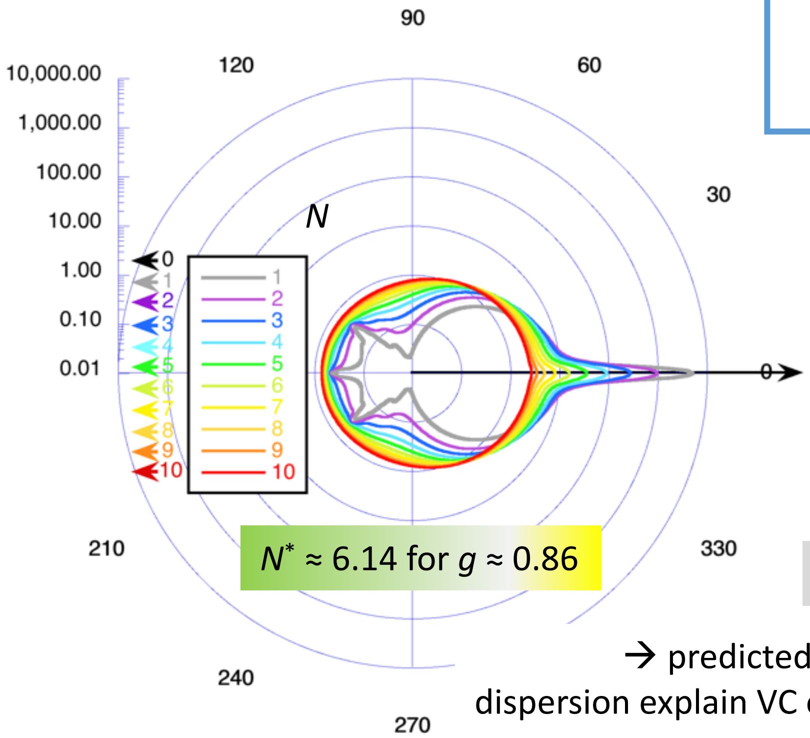
Analytically tractable ← "all-VC" spherical cloud

$R + T = 1$

$R/T = (1-g)\tau_{diam}/2\chi$

Diffusion process [#2]

- random walks unfold in 3D *physical* space
- in the *veiled core*
- gradual loss of *positional* memory
- controls cloud-scale *contrast* between sunny and shady sides

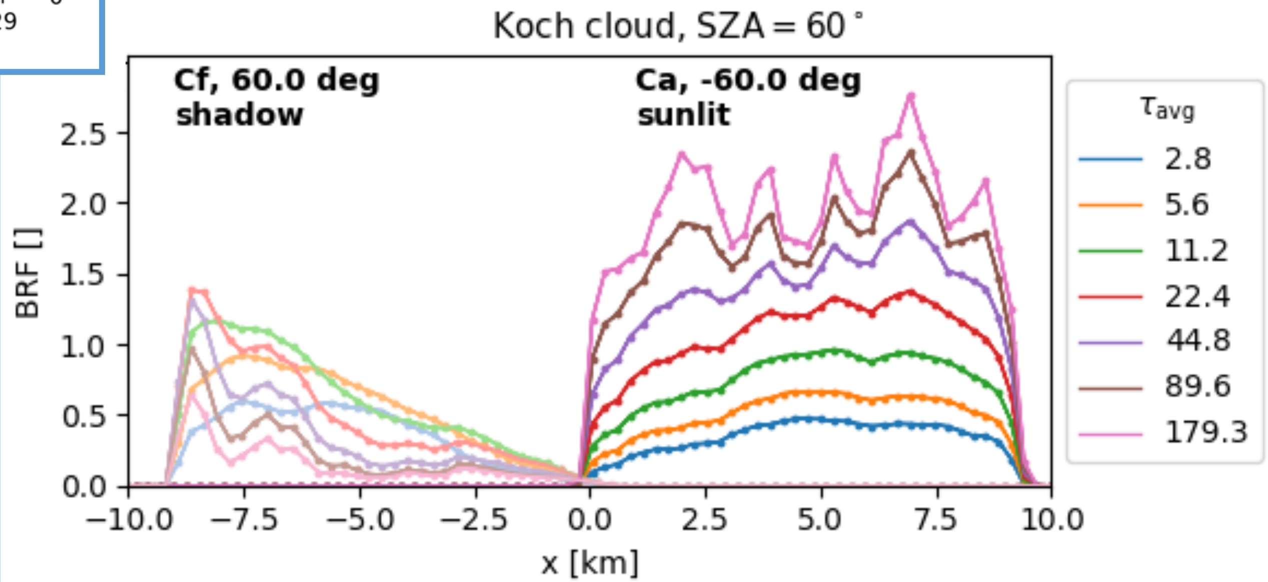


Angular distribution of sunlight after N successive scatterings ($N = 0,\ldots,10$). ←

Memory of the original (solar) direction is all but lost after N^* steps.

$N^* = 1/\ln(1/g) \approx (1/g-1)^{-1}$

→ predicted along-beam drift and lateral dispersion explain VC optical depth threshold at ≈5



sum → T sum → R

To broaden passive VNIR+SWIR cloud remote sensing past stratiform ones, we need full 3D tomographic reconstructions of their convectively-driven counterparts.

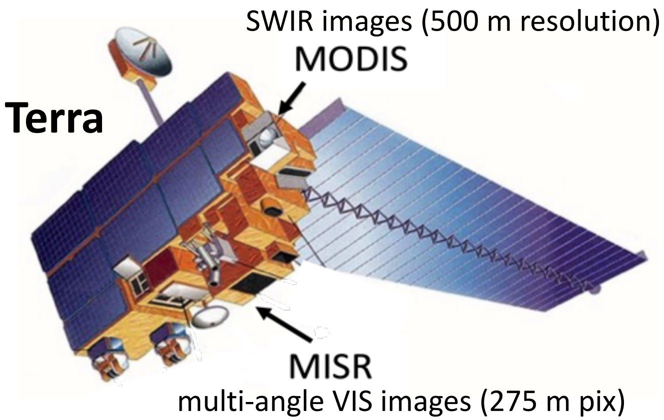
Bi-spectral method: 2 (VIS+SWIR) radiances per pixel → 2 cloud properties (optical depth, effective particle size)
Cloud tomography: multi-angle/bi-spectral images → ~$10^{4.5}$ to~$10^{5.5}$ unknown extinction values, plus microphysics

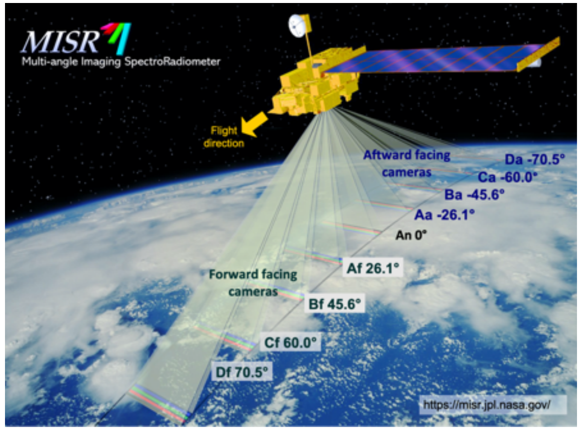
Demonstrated on LES clouds (known truth) and Air[borne]MSPI data (~20 m voxels/pixels) by Levis et al. (2015, 2017, 2020), but space-based (MISR+MODIS) imagers have 250 to 500 m pixels. These pixels will generally be *optically thick* and *hetero-generous*, in patent violation of the assumptions in the current forward model in cloud tomography, SHDOM (Evans, 1996)!

We need: (1) new 3D radiative transfer *forward* model, and (2) new formulation of the large ill-posed *inverse* problem
Starting with: physical insights into exactly how cloud images are formed at solar (VNIR+SWIR) wavelengths → DONE!

This study will enable 3D convective cloud tomography using …

… existing, and …





… future sensors.

NB. Present learnings apply to all manner of solar cloud sensing, naked eyes included.

Science drivers: aerosol, cloud, convection, and precipitation interactions (ie, DS17 A-CCP theme)

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