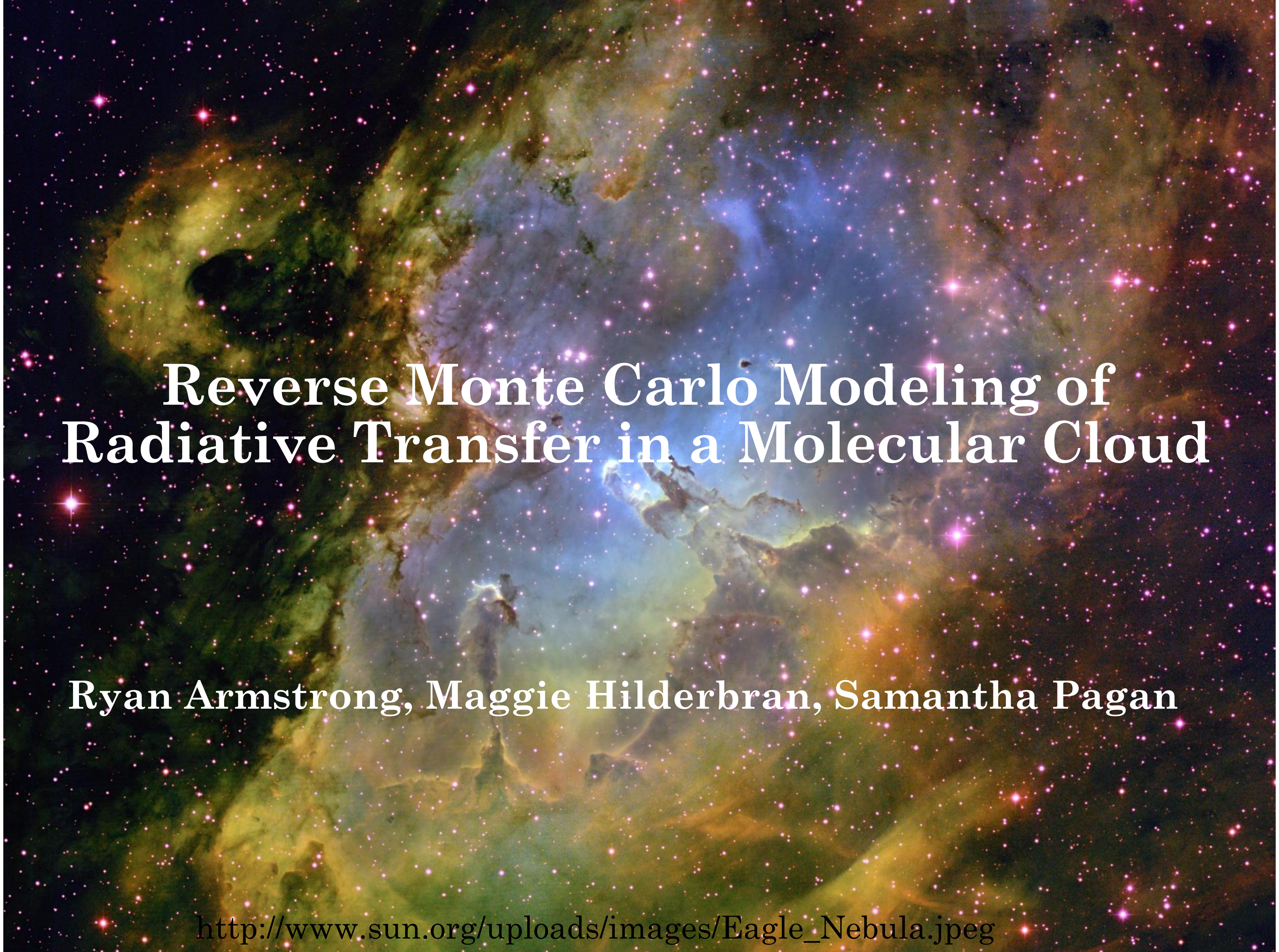


Reverse Monte Carlo Modeling of Radiative Transfer in a Molecular Cloud

Ryan Armstrong, Maggie Hilderbran, Samantha Pagan

http://www.sun.org/uploads/images/Eagle_Nebula.jpeg

Outline

- Molecular clouds and radiative transfer
- Motivation
- Theory
- Methods
- Preliminary results
- Changes
- Mores results
- Lessons learned and conclusions

https://cosmos-magazine.imgix.net/file/spina/photo/11118/170714_Chandra_Full.jpg?fit=clip&w=835

Molecular Clouds

- What is a molecular cloud?
- High density dust and gas
- Molecules may form

http://astronomyisawesome.com/wp-content/uploads/2015/08/giant-molecular-cloud-star-formation.jpg

Connection to 358

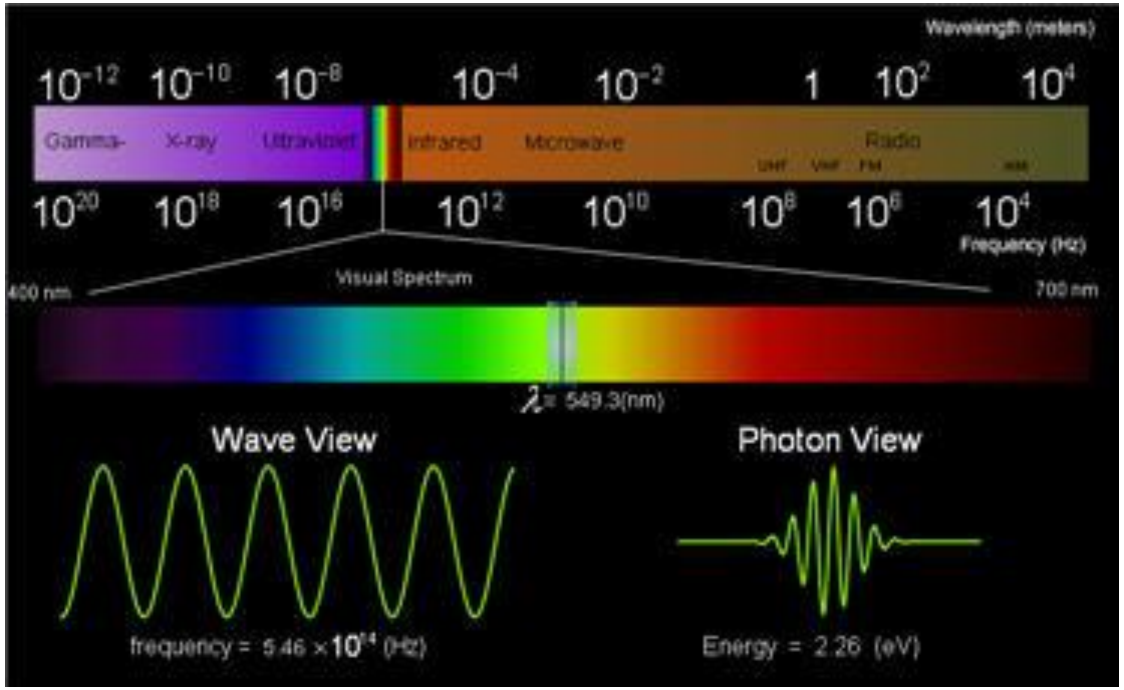
- Remember: HW1 ODE's: Formation of molecular hydrogen H_2 in interstellar gas reaction network

- In a molecular cloud

$$
\begin{aligned}
A + A &\rightarrow B \text{ H}_2 \text{ formation on grains, rate } k_1 \\
B + \gamma &\rightarrow 2A \text{ photo-dissociation of H}_2\text{, rate } k_2 \\
A + \gamma &\rightarrow C \text{ photo-ionization of H, rate } k_3 \\
C + e &\rightarrow A + \gamma \text{ recombination of H}^+ \text{ with free electron, rate } k_4,
\end{aligned}
$$

Radiative Transfer

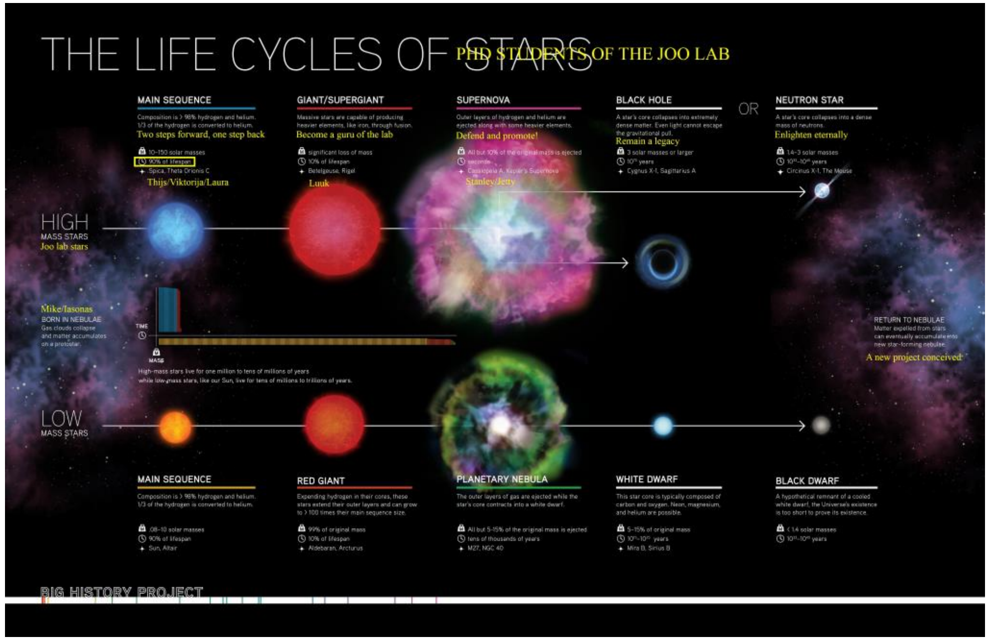
- Photons
- EM radiation
- Emission
- Propagation



http://www.kcvs.ca/martin/astro/au/unit2/51/chp5_1_files/spec1.jpg

Why Study Radiative Transfer in Molecular Clouds?

- Clouds have been challenging to model
- EM radiation is our information about objects in space
- Star life cycles
- Cloud chemistry
- Understand interstellar medium



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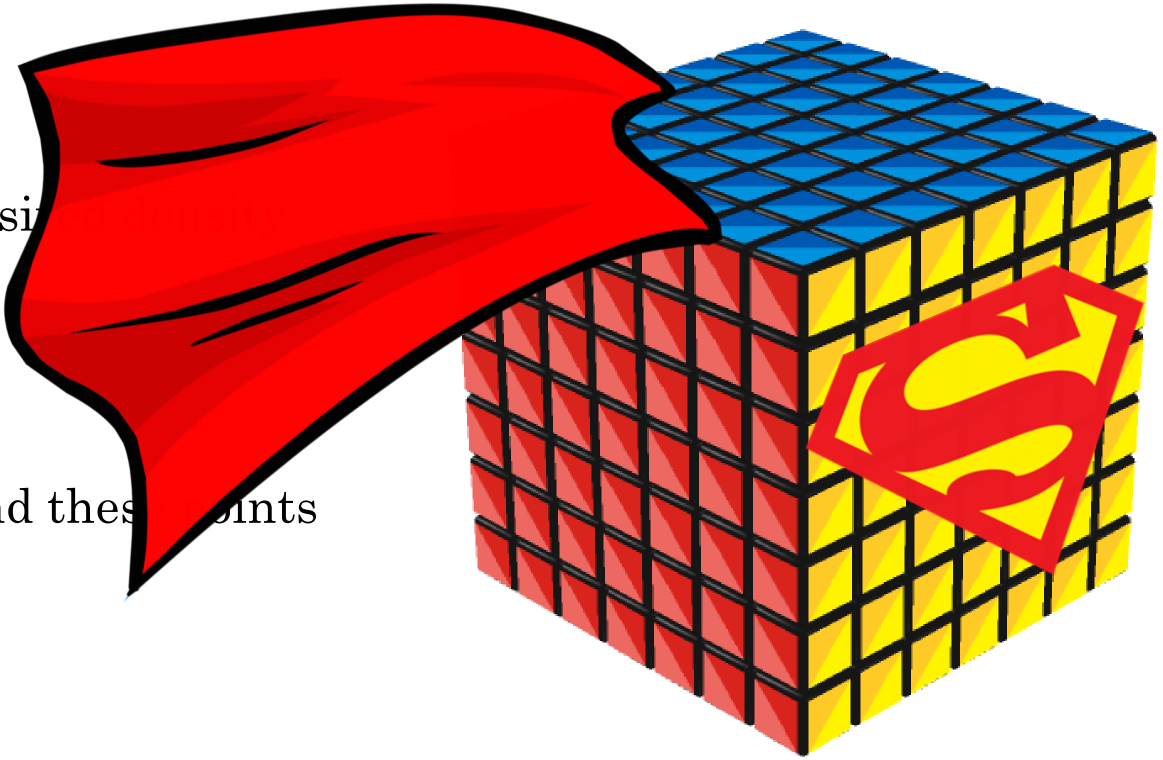
Our Project

1. Create a model cloud
2. Model the transfer of radiation through the cloud
   * Used reverse Monte Carlo
3. View by slicing
4. Adjust parameters

```
import matplotlib.pyplot as plt
import argparse
import scipy.io

# ======================================================================

# random number in a range

def randomnum(high, low):
    randn = np.random.random()(high - low) + low
    return randn


# to make the random points from a sphere in the cloud
def randomdels(sradius):
    randradius = randomnum(0, sradius)
    randtheta = randomnum(0, np.pi)
    randphi = randomnum(0, 2 * np.pi)
    delx = randradius * np.sin(randtheta) * np.cos(randphi)
    dely = randradius * np.sin(randtheta) * np.sin(randphi)
    delz = randradius * np.cos(randtheta)
    return delx, dely, delz

# function make_cloud()
# input:  L      - length of one side of supercube
#         sub    - number of subcubes
#         K      - number of points to be placed
#         D      - fractal dimension D
#         R      - radius of sphere to be inscribed
#         tau_0  - mean optical depth
#         sigma  - cross-section (used for prop.)
#         tol    - tolerance for optical depth (used for prop.)
#
# output: cloud_arr  - 3D array of cloud density
#
def make_cloud(L, sub, K, D, R, tau_0, sigma, tol):
    # placeholder array
    # cloud_arr= 10000*np.ones((sub,sub,sub))

    Npoints = np.zeros((N, 3))
```

Our Cloud

- Goal: To model a clumpy cloud with desired density
- Begin: Grid of cubes→ SuperCube
- Randomly choose N points
- Choose N points within a sphere around these points
- Continue to N^4 points
- Create desired density
- Clumpy Cloud

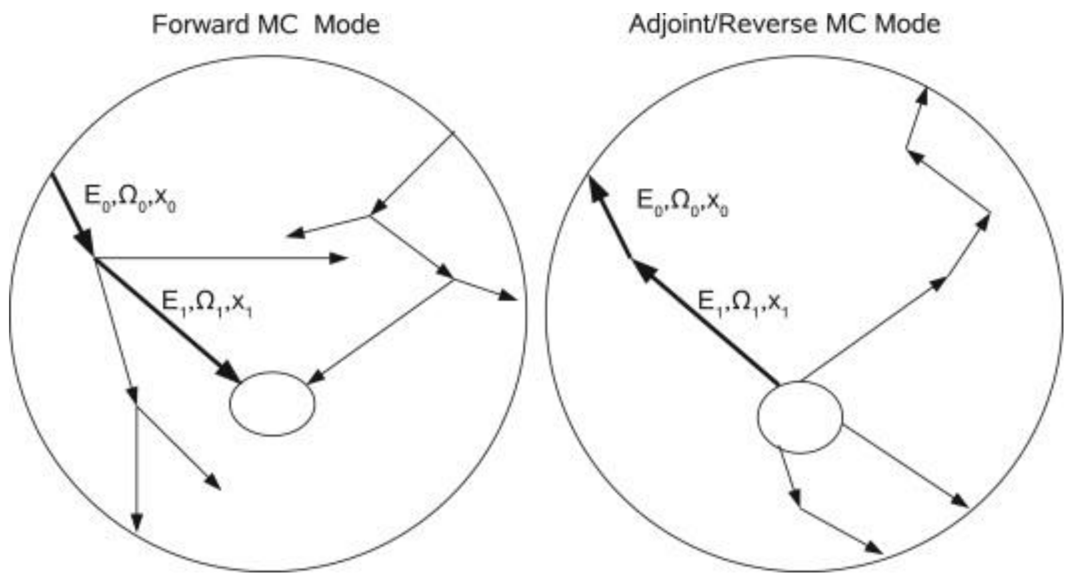


http://www.randelshofer.ch/rubik/virtual_cubes/vcube7/super_cubes/images/screenshots/7x_triangular_super_cube_big.png

Radiative Transfer Through Reverse Monte Carlo

- Reverse Monte Carlo
  - Choosing interior points where photons end
  - Propagate backwards in time to origin
  - Good for probabilistic processes

- Radiative transfer
  - Choose *A* points
  - Propagate outward to edge



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Equations and Key Terms

- Likelihood photon is not absorbed $W = \exp(-\tau_a^{tot})$
- Scattering phase function
  - Sampled through the:

  Trajectory deflection angle

$$\Phi(\theta) = \frac{(1/4\pi)(1 - g^2)}{(1 + g^2 - 2g\cos\theta)^{3/2}}$$

$$\theta(p) = \frac{(1 + g^2) - [(1 - g^2)/(1 - g + 2gp)]^2}{2g}$$

- Optical Depth to next event
- Total absorption optical depth

$$\tau_s = -\ln(p) \quad \tau_s' = \sum \sigma_s(\lambda) n_H \Delta l,$$

$$\tau_a^{tot} = \sum (\omega^{-1} - 1)\tau_s,$$

- ω: Grain albedo.
- g: Asymmetry parameter (dependent on the material in the cloud)
- n: The number density of the cloud.
- $\sigma_{a,s}$: The cross section of the absorbing, scattering material.
- p: The cumulative probability of a photon traveling τ_s before scattering.
- τ_a^{tot}: The total absorption optical depth along a photon's trajectory.
- θ: The trajectory's deflection angle.

More Equations and Parameters

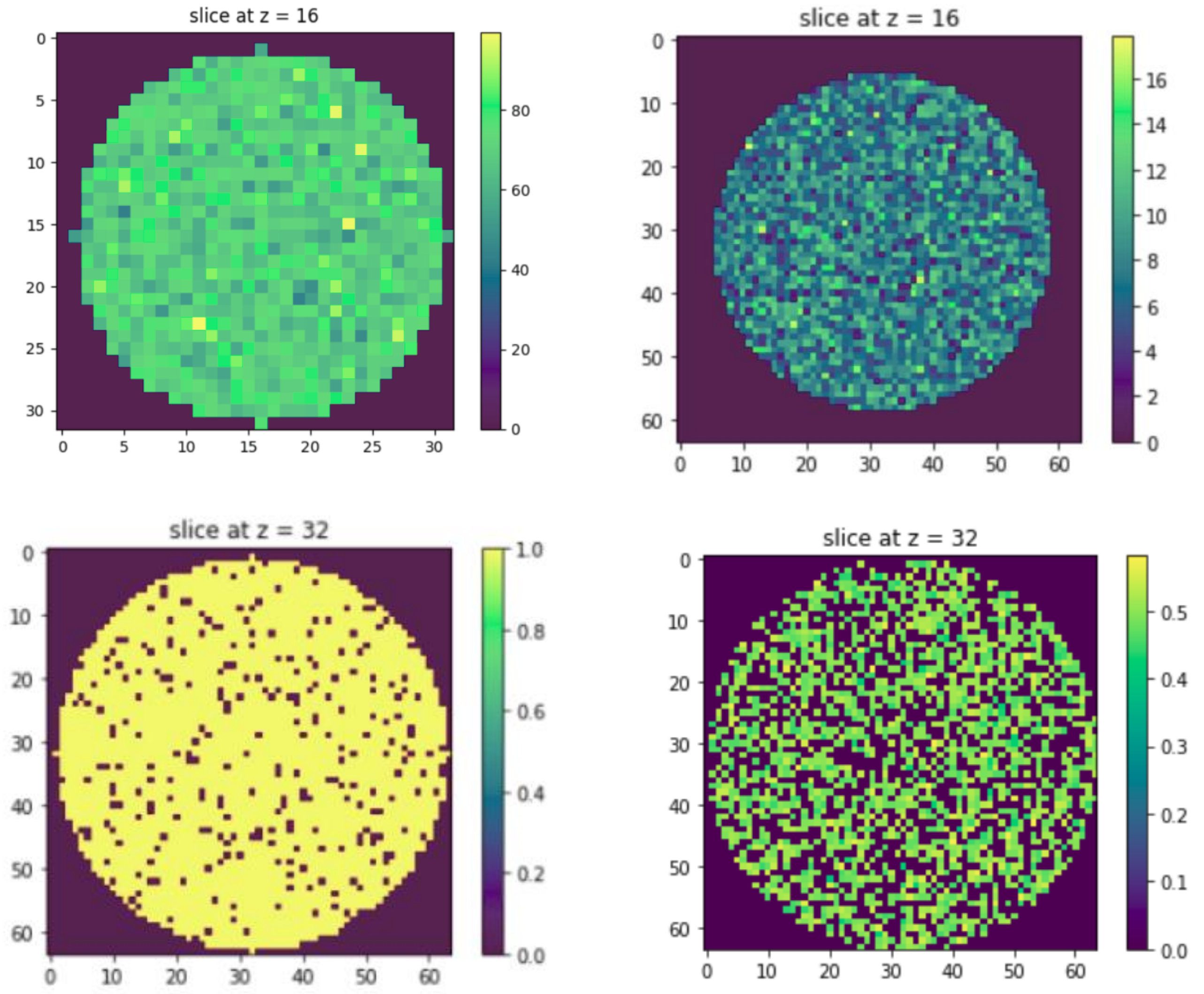
- Mean specific intensity at a point

$$\frac{J(\mathbf{A})}{I_0} = \frac{1}{N}\sum_{n}^{N}\frac{I(\hat{\mathbf{k}}_{\mathbf{obs}}, \mathbf{A})}{I_0} = \frac{1}{NM}\sum_{n}^{N}\sum_{m}^{M} W_{nm},$$

- W: The likelihood a photon is not absorbed along it's trajectory.
- $\mathbf{l}$: The path of the photon.

Our Preliminary Results

- Representation of data:
  - Mean specific intensity
  - Slices along the cloud
  - Choose z
- Problems
  - Random saturation
  - Super saturation
  - Under saturation
- Inconsistent with physics
- Back to the drawing board!



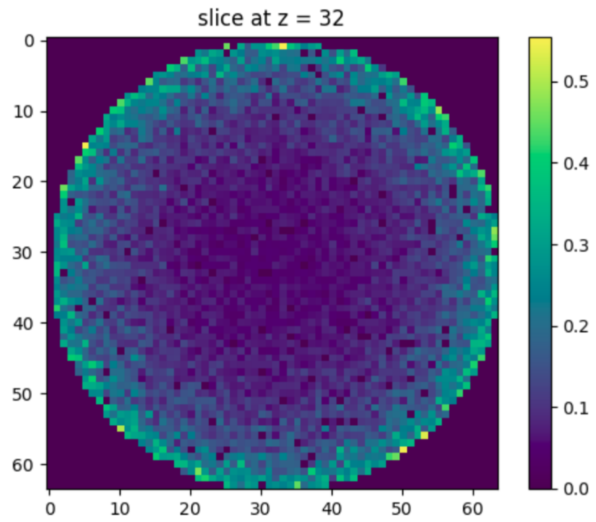
Added Tests and Features

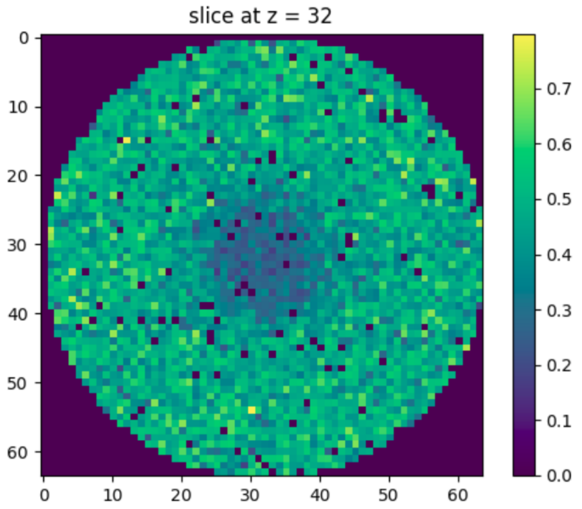
- Hierarchical Test Cloud
- Creating sample clouds
  - Test radiative transfer
- Progress bar and estimation of run time

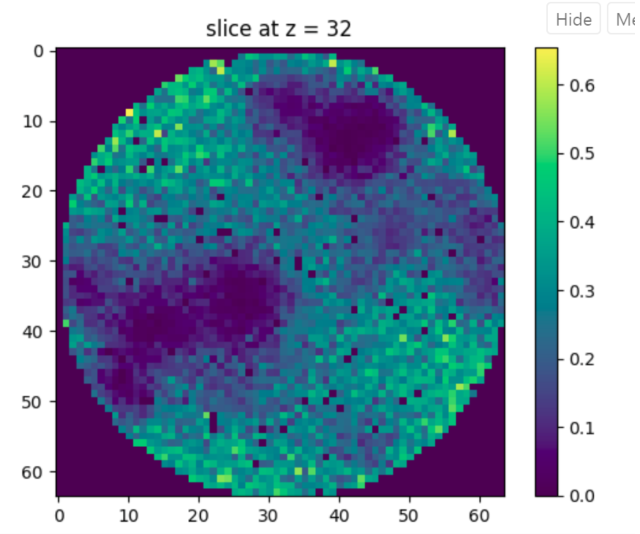
```
In [37]: runfile('C:/Users/ryanaa/Documents/ph
15 300000', wdir='C:/Users/ryanaa/Documents/ph
Points: 1048576
R1: 8.07003891051
R2: 9.26086956522
R3: 8.42608695652
R4: 7.61971830986
R5: 6.27443609023
R6: 3.82573179033
R7: 2.06954137587
R8: 4.38139527131
Proportionality Constant: 0.769674584173
Loop Starting
1%
Estimated Time Remaing 29771.350938762294
5%
Estimated Time Remaing 28427.293000887046
25%
Estimated Time Remaing 22411.615555742905
```

Uniform vs. Clumpy

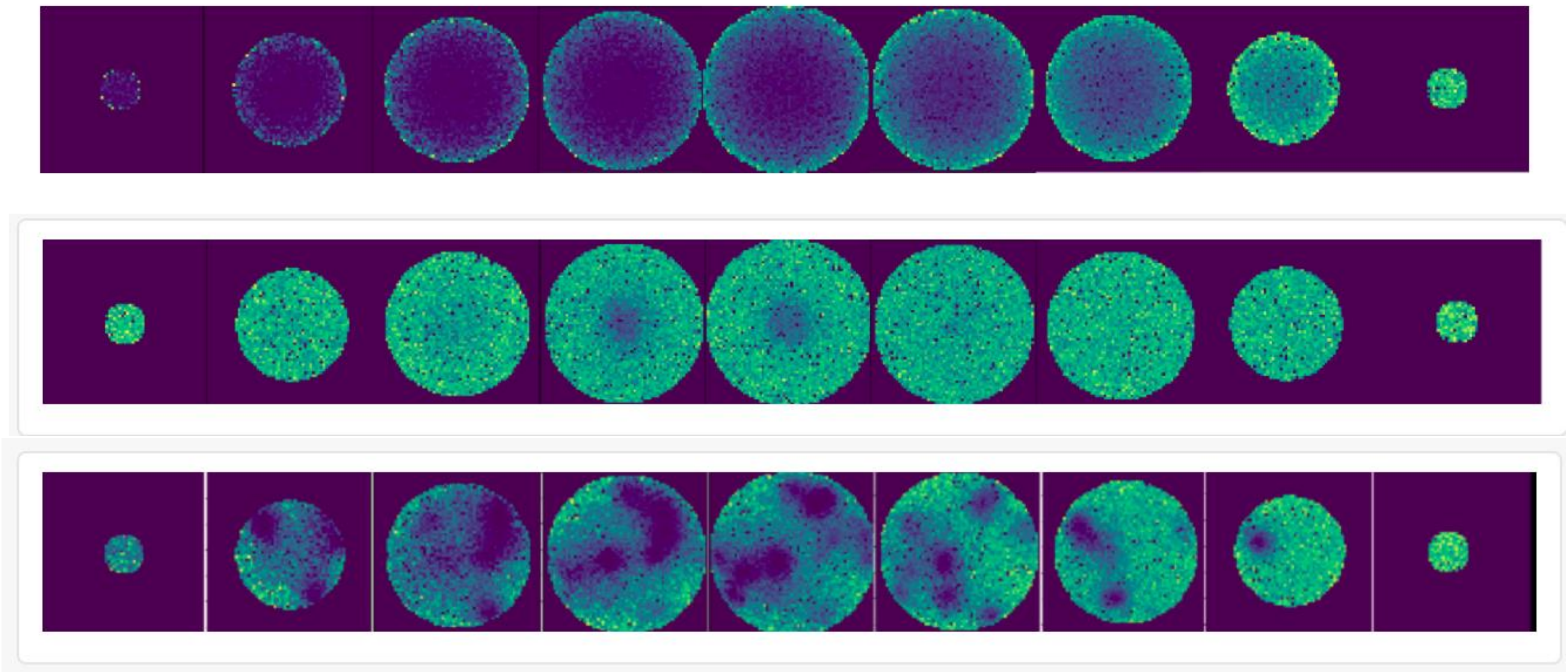
- Application in cloud chemistry



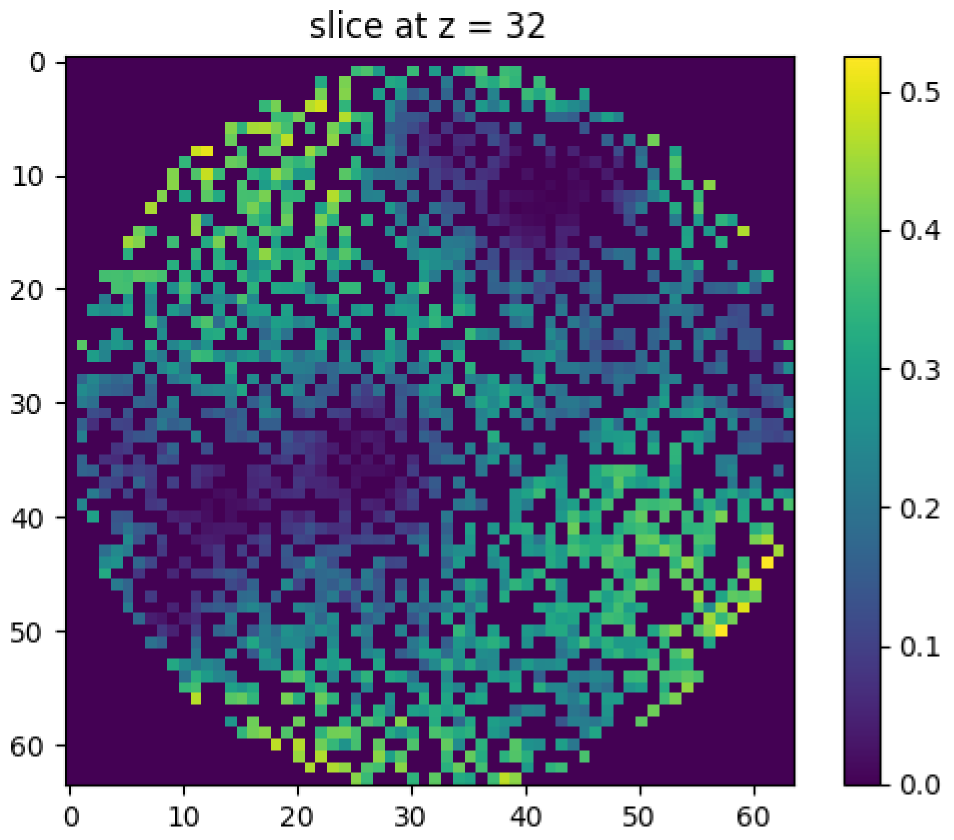




Uniform, Hierarchical, Clumpy



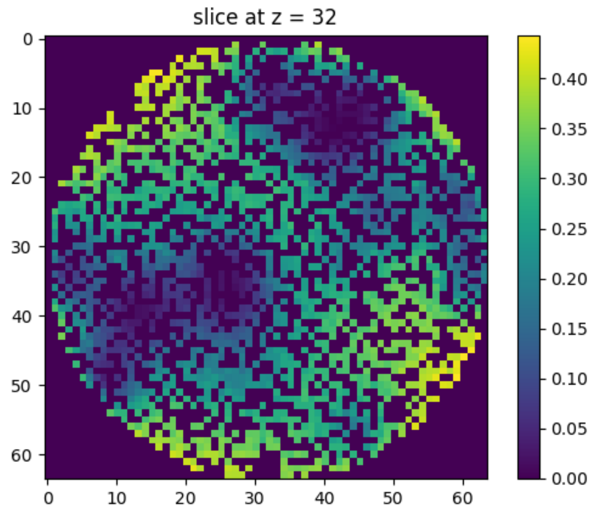
Standard Cloud

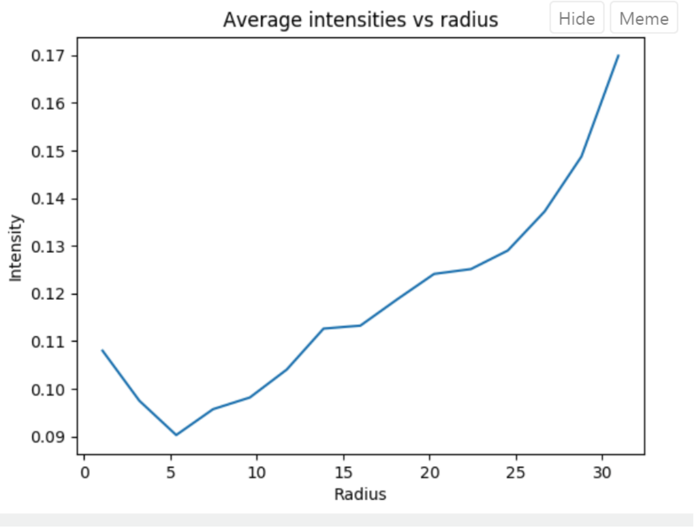


- N=64
- N=10 (direction of observation)
- M=5 (number of trajectories)
- Points=100,000

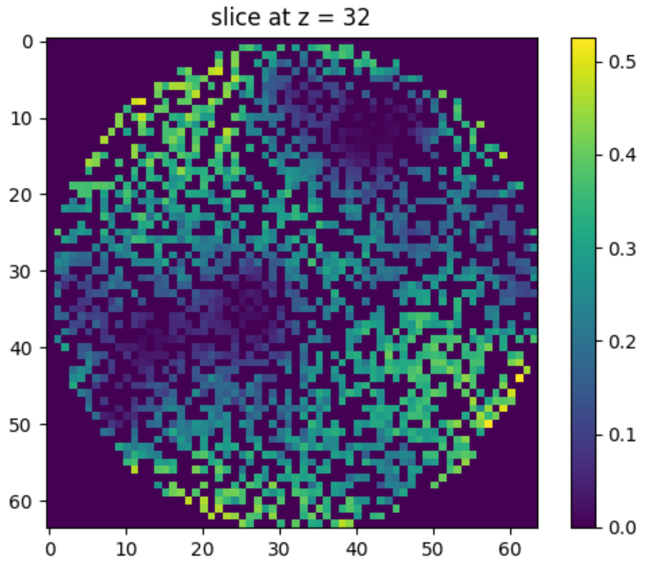
- Ran smaller M and N's to observe change of parameters
- N=10, M=1

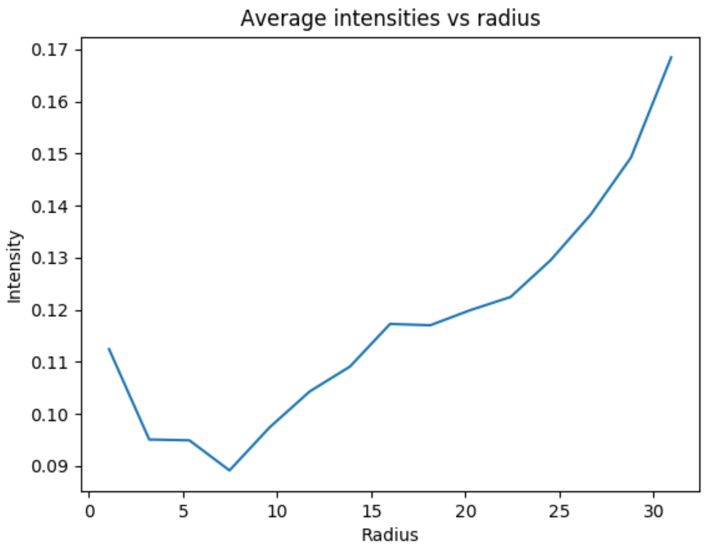
- Longest test N=100 M=10





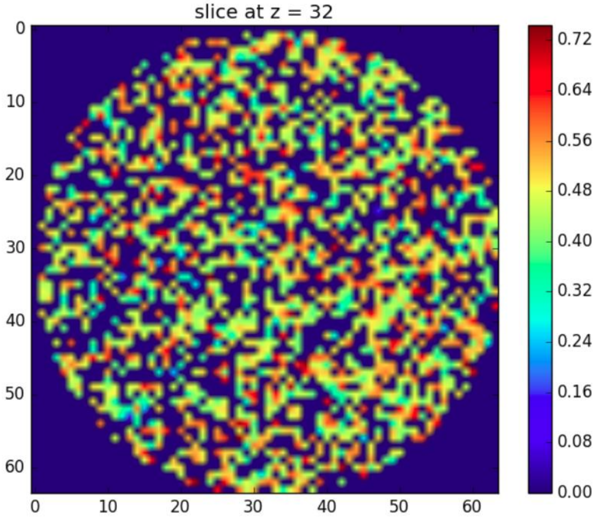
- Standard N=10 M=5

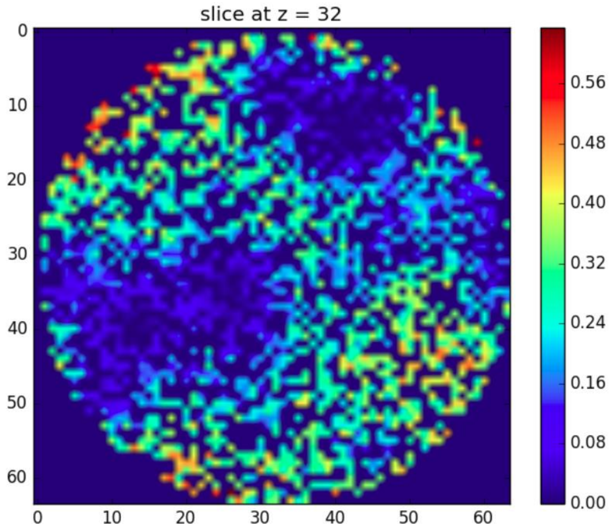


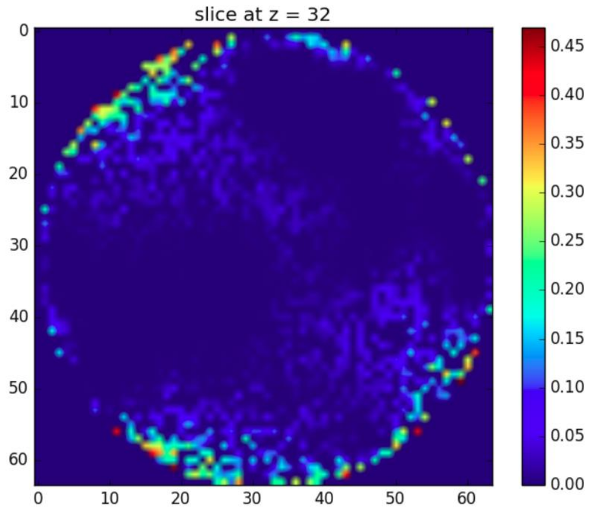


Parameters: Tau

- 0.1 vs. 10

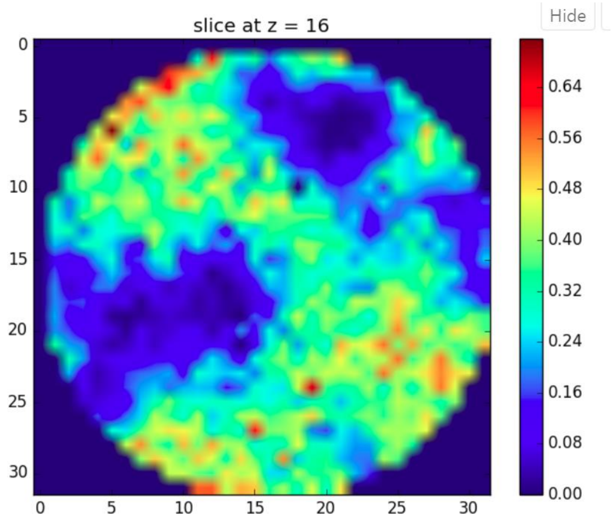


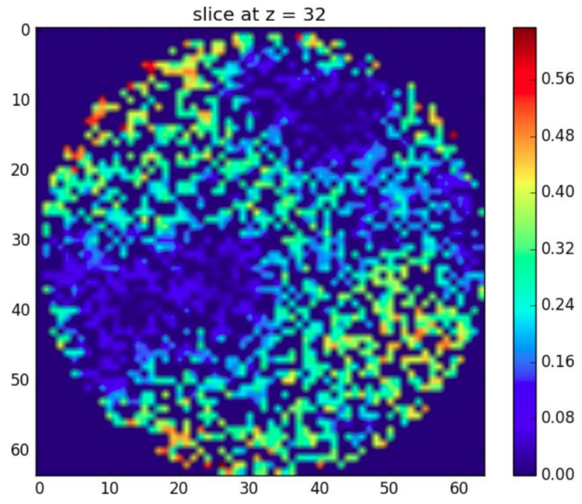


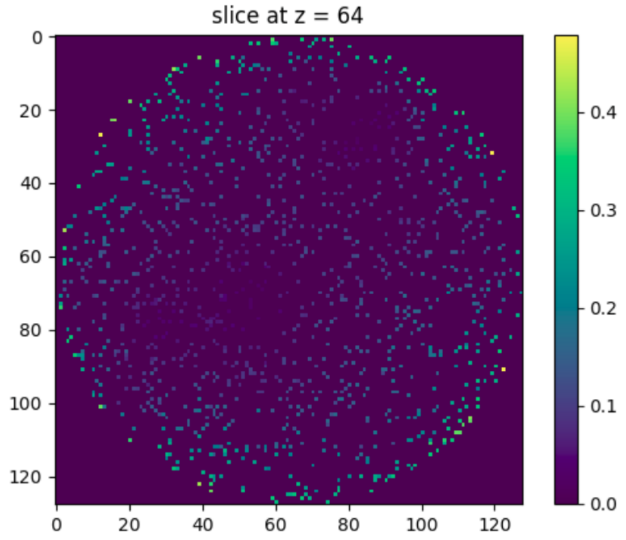


Parameters: Dimensions of the supercube

- 32 vs. 64 vs. 128

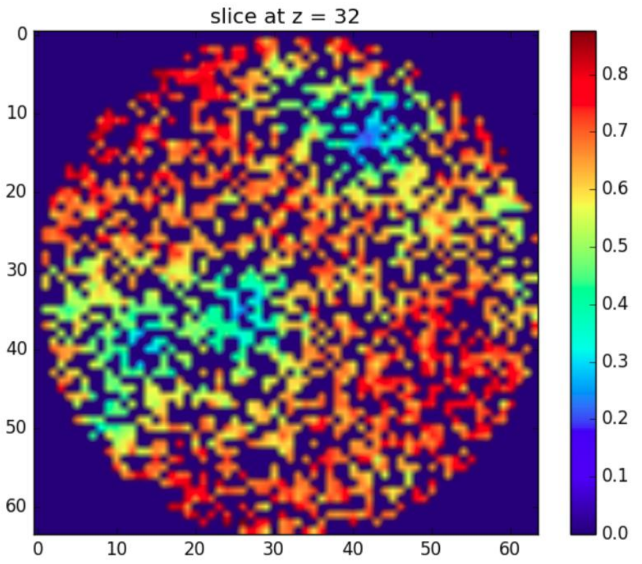


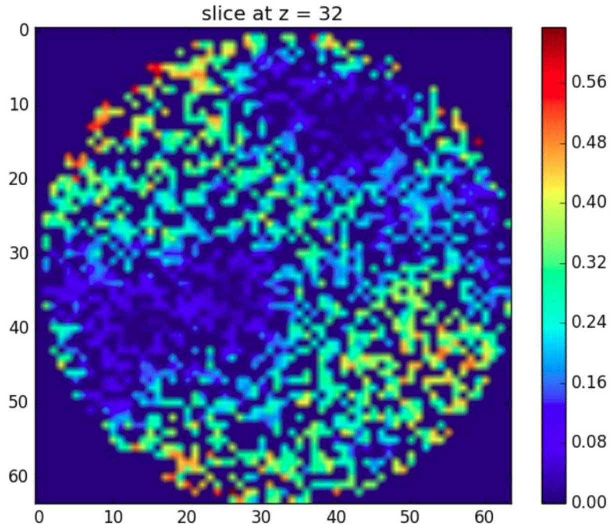


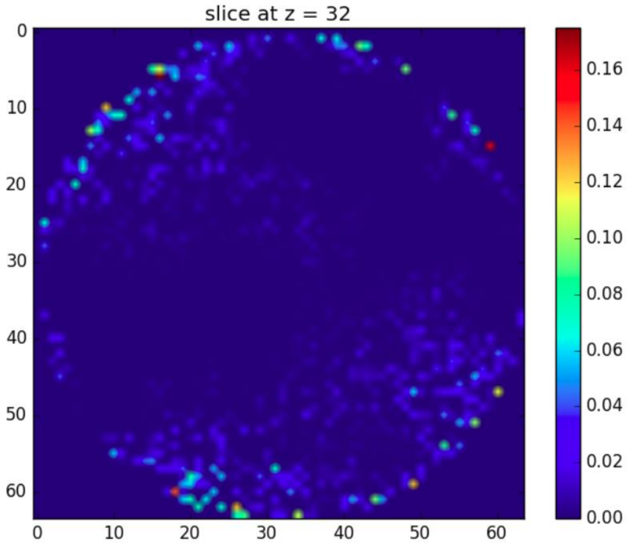


Parameters: Albedo

- 0.8 vs. 0.5. vs. 0.1

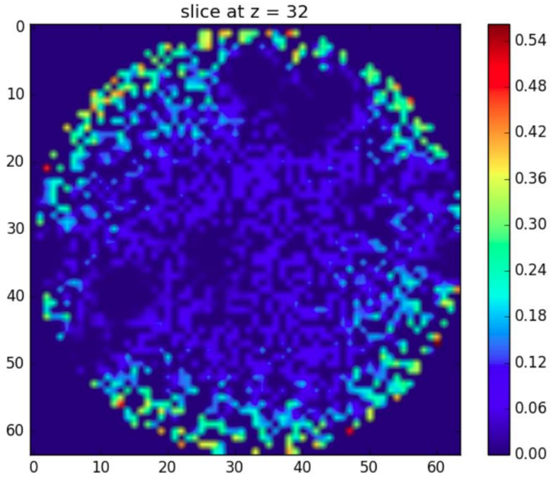


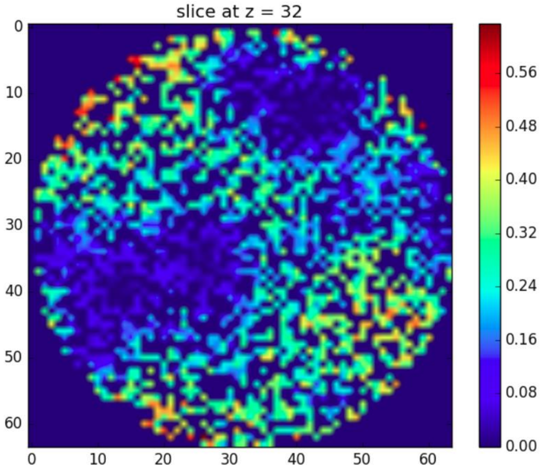


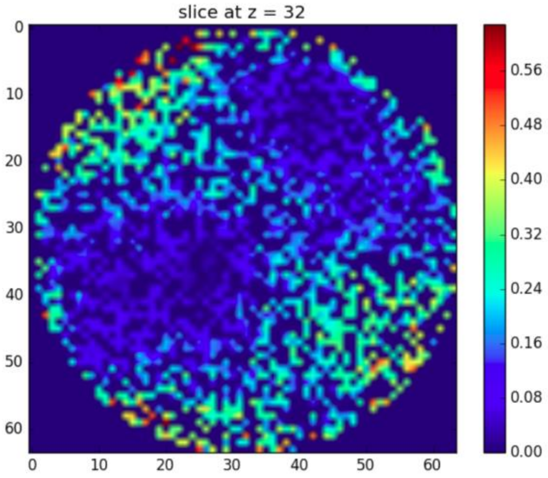


Parameters: Fractal Dimension (D)

- 1.5 vs. 2.3 vs. 3

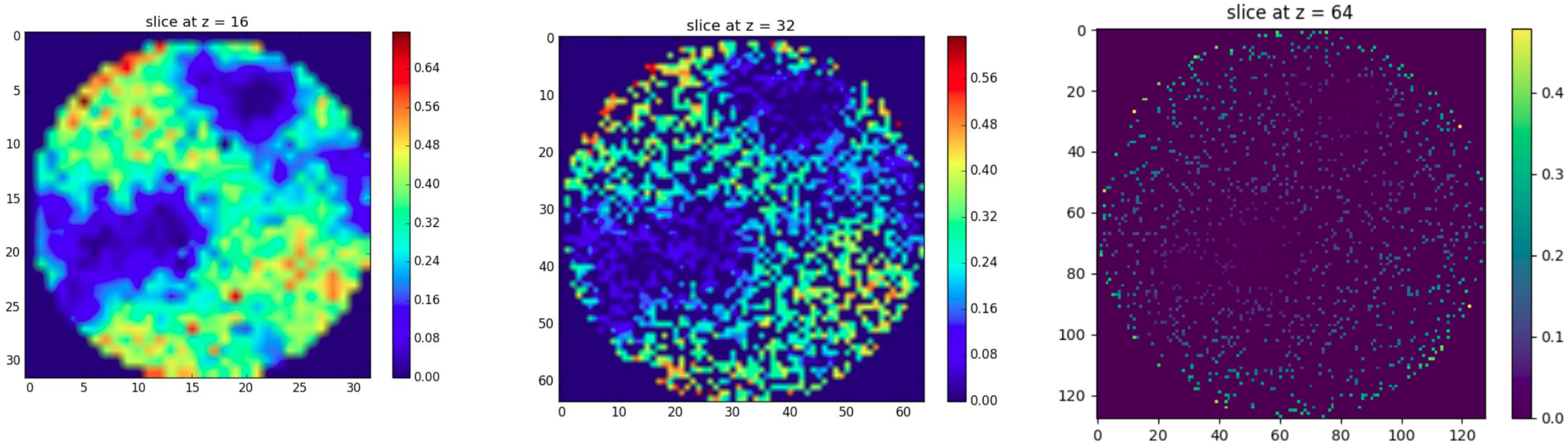






Length of Supercube

- Decided on 64 for runtime
- Compare 32, 64, and 128



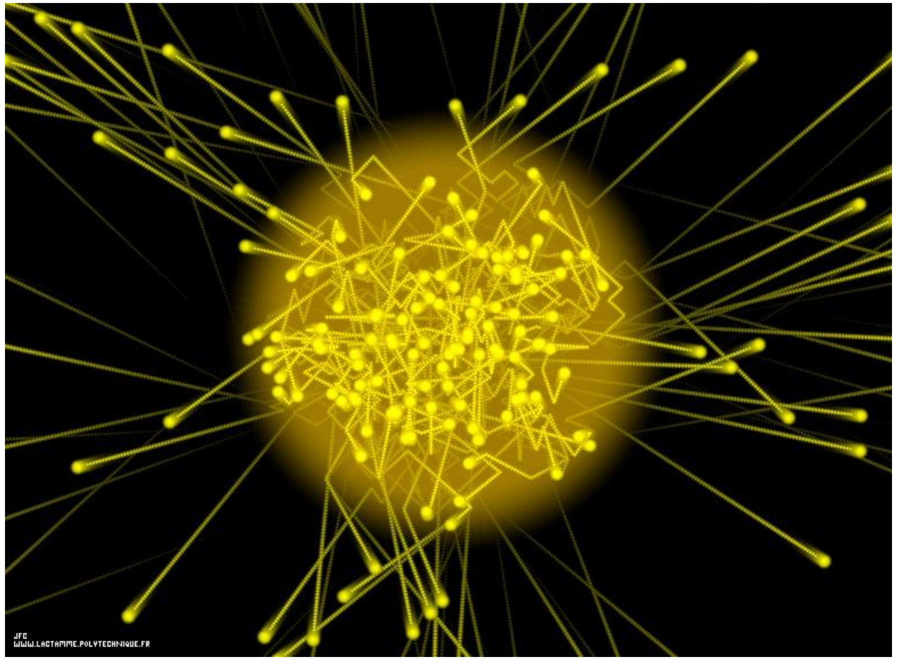
Improvements and Lessons Learned

- Run time and efficiency
  - A HUGE Problem (15 hours)
  - Print statements
  - For loops and while loops
- The effect of parameter values
- Importance of tests along the way

https://media.restorationhardware.com/is/image/rhis/prod640021?PD&illum=0&wid=650

Conclusions

- Clouds are complex to model
- Effects of parameters
- Effects of different cloud models
- Common pitfalls of a cloud code
- Huge limits on computing time
- Scaling to larger research
- More tests on parameters



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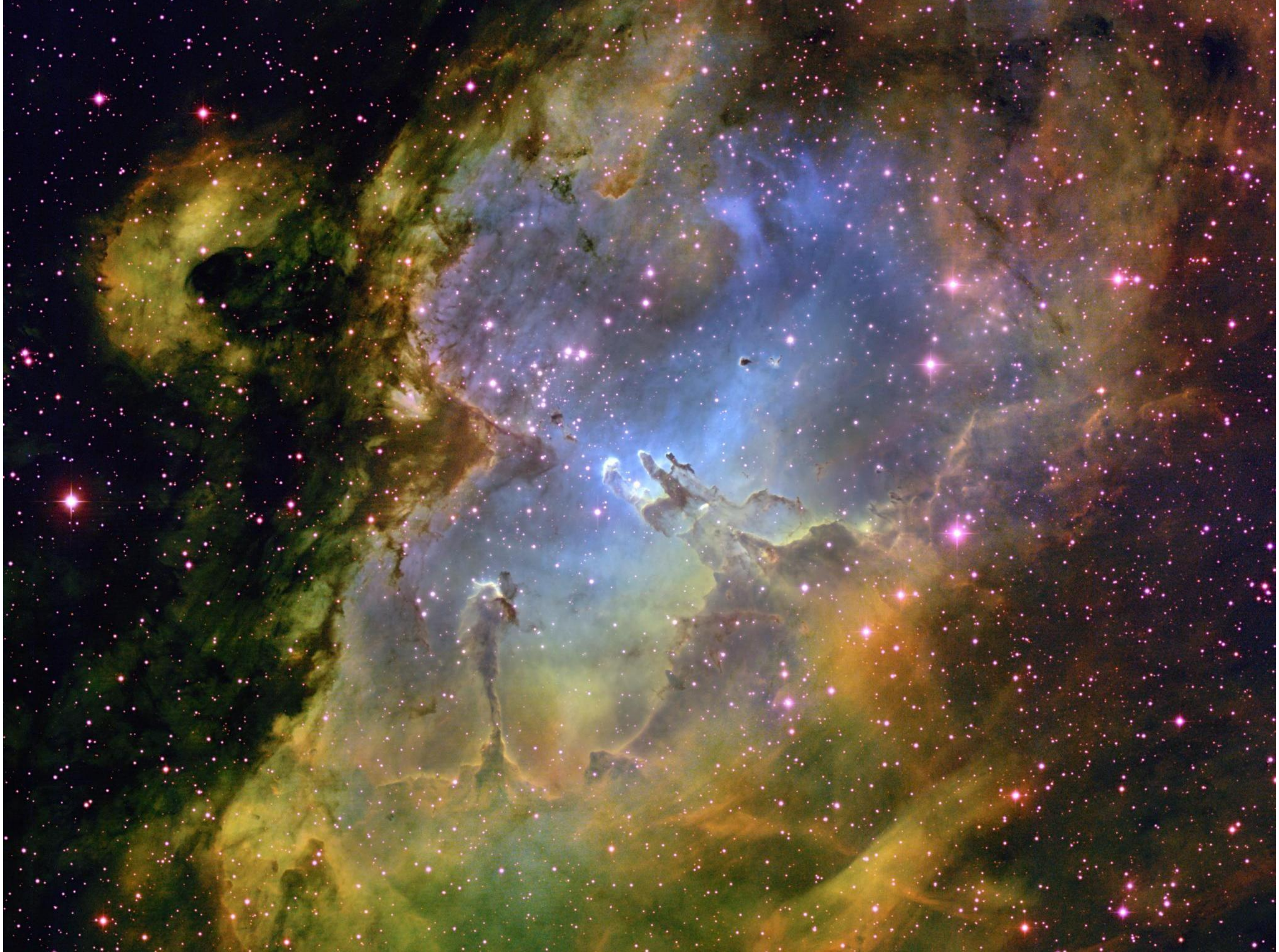

Variables

- τ_a^{tot}: The total absorption optical depth along a photon's trajectory.
- W: The likelihood a photon is not absorbed along it's trajectory.
- τ_s: The optical depth to the next scattering event.
- p: The cumulative probability of a photon traveling τ_s before scattering.
- ω: Grain albedo.
- θ: The trajectory's deflection angle.
- g: Asymmetry parameter (dependent on the material in the cloud)
- n: The number density of the cloud.
- $\sigma_{a,s}$: The cross section of the absorbing, scattering material.
- $\mathbf{l}$: The path of the photon.
- $J(x)$: The mean specific intensity at point x.