Sunrise:
Panchromatic SED Models of Simulated Galaxies

Lecture 4:
Dust emission & Sunrise science

Patrik Jonsson
Harvard-Smithsonian Center for Astrophysics

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Lecture outline

- Lecture 2: Sunrise work flow. Parameters, convergence, other subtleties.
- Lecture 3: Radiation transfer theory. Monte Carlo. Polychromatic MC.
- Lecture 4: Dust emission, dust self-absorption. Sunrise on GPUs. Sunrise science.
Dust models

- Models of dust try to match observations with a physical description of the grains
- Typically composed of:
  - Silicate grains (amorphous SiO$_2$)
  - Carbonaceous grains (graphite)
  - Polycyclic aromatic hydrocarbons (PAHs)
- with a distribution of sizes
- Cross sections calculated from material constants and geometry (spheres)
- See review by Draine (2003)
Dust emission

- For large grains (many hundreds of Å) emission can be calculated as a modified blackbody

\[ L_h = \int \sigma_a(\lambda)B(\lambda, T_e) \, d\lambda = 2hc^2 \int \frac{\sigma_a(\lambda)}{(e^{hc/(k\lambda T_e)} - 1)} \lambda^5 \, d\lambda \]

- But very small grains have such low heat capacity they are heated by single-photon absorptions
  - fluctuate in temperature
  - thermal equilibrium not a good approx.

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Very small grain emission

Emission is broader than if thermal equilibrium is assumed

BUT much harder to calculate

grains are both hotter and colder than one might guess

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PAH emission

A series of narrow features between 5–20 μm

Draine & Li (2007)

currently only modeled as a fixed fingerprint in Sunrise

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Dust self-absorption

Would be straightforward if dust was only heated by starlight

but it’s not – dust absorbs its own emission

need to iterate:

calculate thermal equilibrium $T$
Dust self-absorption: step 1

Calculate the equilibrium temperature of the dust grains

\[ L_{h; c, s} = \int I_c(\lambda) \sigma_{a; s}(\lambda) \, d\lambda \]

heating by absorption of radiation

balances

\[ L_{h; c, s} = 2hc^2 \int \frac{\sigma_{a; s}(\lambda)}{(e^{hc/(k\lambda T_{e; c, s})} - 1) \lambda^2} \, d\lambda \]

cooling by emission of radiation

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Dust self-absorption: step 2

Calculate how much dust emission in the cells contributes to radiation intensity in the other cells.

This is like a normal Monte Carlo pass, only sources aren't stars but the dust.

- and now go back and recalculate temperatures
More on dust self-absorption

Actually, it’s a bit more complicated...

Let’s look at this in more detail:

- The temperature calculation we just talked about can be viewed as a conversion from intensity to luminosity

\[ L_{\lambda} = B_{\lambda} (I_{\lambda'}) \]

- And the transfer of radiation as a conversion from luminosity to intensity

\[ I_{i,\lambda} = \sum_j L_{j,\lambda} T_{ij,\lambda} \]

T is known as the “lambda operator”
More on dust self-absorption

\[ I_{i,\lambda} = \sum_j L_{j,\lambda} T_{ij,\lambda} \]

Problem: we are recomputing the solution from the start each time

Elements of T are subject to MC noise

The resulting intensities will always change within the MC error

Will never “converge”, unless we use very many rays...

Difficult to judge when solution is stationary
Dust self-absorption: a better way

\[ I_{i,\lambda}^{k+1} = \sum_j L_{i,\lambda}^k T_{ij,\lambda} \]

Instead: only transfer the change in \( L \) each MC pass, not the full luminosity

\[ I_{i,\lambda}^{k+1} = I_{i,\lambda}^k + \sum_j \left( L_{j,\lambda}^k - L_{j,\lambda}^{k-1} \right) T_{ij,\lambda} \]

Signal being transferred is now at most as large as previous iteration

Eventually, all \( L \) must leave the box \( \Rightarrow \) scheme must converge

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Dust self-absorption: a better way

Works quite well

The convergence criterion now: less than a specified fraction of the original luminosity left in the grid
This is expensive, though...

\[ L_{h;c,s} = 2hc^2 \int \frac{\sigma_{a;s}(\lambda)}{\left(e^{hc/(k\lambda T_{e;c,s})} - 1\right) \lambda^2} \, d\lambda \]

Need to do this for \(10^6 - 10^7\) grid cells and 100 wavelengths, for about 10 iterations, for each pass

= Evaluating A LOT of exponentials

temperature calculation actually takes much longer than the ray tracing...

(Yes, you can make a table... bear with me!)

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...use a GPU to speed it up

- Graphics processors are now fully programmable, massively data-parallel machines
- Raw floating-point performance is many times larger than that of CPUs
- But small or non-existent cache – sensitive to memory layout
- Double-precision performance $\ll$ single
- Can be programmed in a C-like language (CUDA/OpenCL)
Temperature calculation is perfect for a GPU
Massively parallel, floating-point intensive
Has been ported to run on Nvidia GPUs with CUDA (Jonsson & Primack 2010)
Each core will calculate the temperature for one specific cell and dust species

\[
L_{h;c,s} = 2hc^2 \sum_l \frac{\sigma_{a;s,l} \Delta \lambda_l}{(e^{hc/(k\lambda_l T_e;c,s)} - 1) \lambda_l^5}
\]
GPU (Tesla C1060) is $69\times$ faster than 8 Xeon cores!

The GPU is even $16\times$ faster than the CPU doing interpolation!
Sunrise results

do these galaxies actually look real?
Remember these guys?

Simulated these in isolation for 1 Gyr, observed from many inclinations and bands

Now let's compare them to the SINGS sample

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Matching SEDs with SINGS galaxies

SINGS data from Dale et al 07

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Comparing to SINGS: UV-NIR

color indicates nuclear type (orange: SB; green: LINER; blue: Sy; purple: n/a)
Comparing to SINGS: NIR-FIR

SLUGS from Willmer et al 09.

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Origin of 850\(\mu m\) mismatch?

- Draine et al finds NO dust at <1U in any of the SINGS galaxies
- Sbc galaxy has 60%
- Setting an intensity floor of 5U decreases discrepancy
- But how do you get a galaxy with no dust at low radiation intensities?
Origin of 850μm mismatch?

Dale & Helou (2002) find same mismatch with ISO/IRAS/SCUBA in their (much simpler) models
Solve this by assuming a different cross section at long wavelengths
instead of $\kappa \sim \lambda^{-2}$
they use $\kappa \sim \lambda^{2.5-0.4\log U}$
dust properties change with environment
But what about the SLUGS galaxies?
they might be missing galaxies with less cold dust due to 850μm flux limit
The small sample size of SINGS might not have picked up this population with more cold dust
Comparing to SINGS: IRX-β

The spatial variations of the dust emission in the SINGS galaxies were studied by Bendo et al. (2008), who investigated emission from PAHs, measured at $8\,\mu\text{m}$. They found that the PAH $8\,\mu\text{m}$ surface brightness ratio, $L_{8\,\mu\text{m}}$, was well correlated with $L_{24\,\mu\text{m}}$ surface brightness ratio, $L_{24\,\mu\text{m}}$. They interpreted the agreement may break down when looking at individual regions in the Bendo et al. (2008) sample, and the pixel size set to 0.5 kpc. The analysis was restricted to the face-on galaxies to match the galaxies in the Bendo et al. (2008) sample, and the pixel size set to 0.5 kpc.

The spatial variations of the dust emission in the SINGS galaxies were also studied by Jonsson (2004). However, as discussed in Section 2.2, the simulations with very red UV slopes and low values of IRX, well below the SINGS galaxies, are from the G0 galaxy with its very low SFR.
Star-Formation Rate indicators

Using SFR calibrations of Kennicutt (1998)

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Spatially resolved colors: 8/24

Bendo et al. 2008

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Spatially resolved colors: 8/160

Bendo et al. 2008

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Sunrise applications

just a few examples
Merger identification calibration

Can measure sensitivity of merger detection methods on simulations

Lotz et al. (08, 10a, 10b)
Bulge/disk decompositions

- Compare kinematic bulge/disk decomposition (as done in simulations) to photometric (as done in observations)
  - Governato et al (09)
  - Scannapieco et al (10)
- Conclusions unclear at this point
Identifying high-redshift populations

Test if simulated merging galaxies would be selected as DOGs (Dust Obscured Galaxies) or SMGs (Submillimeter Galaxies)

Narayanan et al. (09, 10)

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Summary

- Sunrise is a useful tool for making observational predictions from simulated galaxies.
- Outputs match properties of observed galaxies well, but some discrepancies exist.
- Real galaxies make up a more diverse set than the simulations.
- Simulated galaxy population or dust properties?
- I hope you now have a good grasp of what Sunrise is capable of and how to use it.