Studying Reionization using GPUs

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Radiative Transfer

- Radiative feedback in starforming regions
- Winds on galactic scales
- Reionization
Radiative Transfer
Radiative Transfer

- Radiation field described by intensity function $I(x,n,v,t)$

- Boltzmann equation:
  $$\frac{\partial I}{\partial t} + c\nabla (nI) = \left. \frac{\partial I}{\partial t} \right|_{\text{sources}} - \left. \frac{\partial I}{\partial t} \right|_{\text{sinks}}$$

- Methods: Ray Tracing, Moment based methods, Monte Carlo

- Discretize intensity $I(x,n,v,t)$
  - cartesian grid
  - angular cones
  - one or more frequency bins
Angular Discretization

- Tessellate sphere into equal angle cones
- Each cone field is advected individually
- Advection direction: Cone center $h$
- To fill out cones: smear out advection direction $n$
- Photon conserving advection using Finite Volume methods:
  \[ F = cnI \Delta t \]
Angular Discretization

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\[
F = c n I \Delta t
\]

Chemical Network

\[ \frac{dI}{dt} = -c \sigma n_H \tilde{n}_{HI} I \]

\[ \frac{d\tilde{n}_{HI}}{dt} = \alpha(T)n_H\tilde{n}_e \left(1 - \tilde{n}_{HI}\right) - \beta(T)n_H\tilde{n}_e\tilde{n}_{HI} - c \sigma \tilde{n}_{HI} I \]

ionization

recombination

collisional ionization

\[ \frac{du}{dt} = \epsilon \gamma c \sigma \tilde{n}_{HI} I - C(T) \]

heating

cooling

\[ T = u \frac{2}{3} \frac{m_p}{k_B (2 - \tilde{n}_{HI})} \]
Graphics Processing Units

- Graphics Processing Unit
- Less chip space used for control logic, more space for execution units
- Requires different paradigm of parallelization
- Computations are offloaded from the CPU to the GPU
- Modern trend in high performance computing
Graphics Processing Units

- Modern trend in high performance computing

TITAN (now #2 in TOP500):
CPUs: 18,688 AMD Opteron 6274 16-core CPUs
GPUs: 18,688 Nvidia Tesla K20X GPUs
27 petaFLOPS theoretical peak performance
Coupling to Hydrodynamics

- Radiative transfer is included in cosmological hydrodynamical simulations only recently
- Couple our implementation dynamically to AREPO
- Sub-cycling of radiative transfer step is required
- Offload expansive radiative transfer computations to GPUs
Test Problems

- **Strömgren Sphere:**
  Density $n = 10^{-3}$ cm$^{-3}$
  Temperature $T = 10\,000$ K
  Point source $\dot{N} = 5 \times 10^{48}$ s$^{-1}$

- **Dense clump:**
  Density $n = 0.04$ cm$^{-3}$
  Temperature $T = 40$ K
  Source strength $F = 10^6$ s$^{-1}$ cm$^{-2}$
Test Problems

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Test problems taken from Iliev et al. 2006
Reionization in Cosmological Boxes
Cosmological Boxes

- Simulate the evolution of a cosmic density field without radiative transfer first

- Output from AREPO simulation binned onto a cartesian grid

- Radiation field added in post processing

- Sources of UV photons are given by stellar population

- Density field and source strengths are continuously updated
Cosmological Box: Sub-Volumes

- Here: Resimulation of 4 sub-volumes of a larger cosmological box (→ see Shy Genel’s talk)

- High spatial and temporal resolution for these 4 sub-volumes affordable

- RT Grid: 16.7 million cells

- Box sizes: 5 Mpc/h - 8 Mpc/h

- Most massive halos: $10^{12}$-$10^{13}M_\odot$

- Assumed escape fraction: $f_{esc} = 0.25$
Star Formation Rate

\[ \text{SFR} \left[ \frac{M_\odot}{\text{yr/} \text{Mpc}^3} \right] \]

\[ z \]

- sub-box 0
- sub-box 1
- sub-box 2
- sub-box 3
- full box
Visual Overview
Progress of Ionization
Progress of Ionization

\[ \text{sub-box 0} \]

\[ \log \rho \]

\[ z \]

\[ n_{\text{HII}} \]
Progress of Ionization
Temperature Slices

\[ \log T \left[ K \right] \]
Thomson Optical Depth $\tau$

Planck
sub-box 0
sub-box 1
sub-box 2
sub-box 3
Size Statistics of Ionized Regions

Sub-box 2

\( \log r \)

\( z \)

\( V/V_{\text{ion}} \)
Size Statistics of Ionized Regions
Summary

- New radiative transfer implementation using GPUs
- Plausible reionization histories
- Highest density regions ionize first
- Detailed study of progress of ionization in the full box will follow