The SPHINX simulations of the first billion years and reionisation

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with Blaizot, Chardin, Garel, Haehnelt, Katz, Keating, Kimm, Michel-Dansac, Ocvirk, Sijacki, Teyssier

PNCG 2017

Cosmological radiation-hydrodynamical simulations resolving the ISM of atomically cooling haloes down to $z=6$

13.6 million cpu-hours allocated by PRACE in April 2017 — we are finishing the main simulations
The first billion years

Dark ages: Dark matter collapses to sheets, filaments and clusters.

Atomic matter flows into the gravitational potentials created by dark matter

First galaxies and stars

Credit: Andrey Kravsov, University of Chicago

Cosmic microwave background, as observed by the WMAP satellite

- Surface of last scattering: Atoms combined and Universe became transparent
- Tiny fluctuations in matter density
- Wealth of information about Universe: 1/6 baryons (atoms), 5/6 dark matter

First stars and reionization

- A neutral and metal-poor Universe becomes ionized and metal-rich
- We know it happened, but not so much how and when, even why

Credit: Abraham Loeb, Univ. Colorado
Project goals

• Understand the process and sources of reionisation

• Understand how patchy reionisation affects the growth of satellite galaxies

• Model observational Lyman-alpha signatures of galaxies (RASCAS..see earlier talk by J.Blaizot)

• Predict luminosity function and galaxy distribution at extreme redshift for the JWST era

• Obtain statistical understanding about radiation escape from the ISM (connection to feedback, halo mass)
  • First: What do binary stars have to do with reionisation?
Binary Stars Can Provide the “Missing Photons” Needed for Reionization

Xiangcheng Ma,1* Philip F. Hopkins,1 Daniel Kasen,2,3 Eliot Quataert,2 Claude-André Faucher-Giguère,4 Dušan Kereš5 Norman Murray6† and Allison Strom7

• Post-processing pure-hydro zoom simulations, Ma et al. predict 4-10 times boosted $f_{\text{esc}}$ (escape of ionising radiation) with a binary population SED

• The reason: longer and stronger radiation due to mass transfer in binary systems
SED models
Spectral Energy Distributions for stellar populations

- BPASS = Binary Population and Spectral Synthesis from Eldridge et al.

→ SPHINX: using full RHD cosmological simulations, what does BPASS do for the reionization history?

Before: Radiation absorbed by dense ISM

~ 3 Myr: Massive stars start to explode

After: ISM disrupted and radiation escapes

Graph showing the change in luminosity and ionization over time for different models.
SPHINX
simulation code
and setup
Cosmological code: RAMSES
Teyssier (2002)

Adaptive Mesh Refinement (AMR) for self-gravitating fluid flows

- AMR allows the calculation to be focused on regions of interest.
- The simulation volume can be split and run in parallel on thousands of CPUs.
- Cosmology, dark matter, gas, and stars are included.
- I spent my PhD on adding the propagation of radiation and its interactions with gas, see Rosdahl et al. (2013), Rosdahl & Teyssier (2015).
RAMSES-RT
Radiation Hydrodynamics in RAMSES

- Moment method to propagate photons, allowing an unlimited number of sources
- Photons are emitted and propagated on-the-fly. They ionise, heat, and push the gas, and multi-scatter on dust
- Variable speed-of-light and subcycling of radiation makes for enormous efficiency

⇒ Only existing code that can simulate large-scale reionisation while resolving individual galaxies
- Public, as part of RAMSES, and used in over 20 papers
SPHINX simulation

- 5 cMpc box with high mass resolution
- 10 cMpc box with lower mass resolution (but same physical resolution)
- ...plus many tiny 1.25-2.5 cMpc boxes for exploration and calibration
**SPHINX setup**

- **Physical resolution** max 10 pc, required to capture the escape of ionising radiation from galaxies (Kimm et al, 2017).

- **DM mass resolution** of $3 \times 10^5$ (8 times less in 5 Mpc box). $10^8 \, M_\odot$ halo has 300 (2,500) particles $\gg$ all potential reionisation sources are resolved.

- **Stellar particle resolution** of $10^3 \, M_\odot$ (particle = a stellar population)

- **Bursty turbulence-dependent star formation** (Devriendt et al, in prep)

- **SN explosions** modelled with momentum kicks (Kimm et al., 2015)

- **No calibration on unresolved $f_{\text{esc}}$** (i.e. we simply inject the SED luminosity)

- We run with binary and single star SEDs
SPHINX compared to previous reionisation works

Volume needed to capture $10^{12}$ $M_\odot$ halos

Cosmological homogeneity scale

High resolution: $f_{\text{esc}}$ can be predicted

Low resolution: $f_{\text{esc}}$ is a calibrated parameter
SPHINX results
Full 10 cMpc box, binary SED:
10 cMpc box, binary SED, a closer look
Luminosity function

$z=6$ luminosity function

$\phi_M [\text{cMpc}^{-3} \text{ Mag}^{-1}]$

$M_{AB}$
Reionisation history
binary vs single SEDs

Much more efficient reionsiation with binary populations, independent of box size and mass resolution.
Effect of more IGM photons with binary populations
What are the sources of reionisation?

Working on that, but first hypothesis is intermediate mass halos, since boxes of different sizes and resolution produce very similar reionisation histories.
Summary and future

• The SPHINX simulations are the first fully cosmological RHD simulations that resolve the ISM of galaxies

• Stay tuned for pilot paper:
  • Stellar populations with binary stars really speed up reionisation!

• More papers to follow:
  • Lyman-alpha signatures of simulated galaxies
  • Statistical analysis of escape fractions
  • Which galaxies contribute to reionisation
  • Suppression of galaxy growth in ionisation bubbles
  • Metal-enrichment of the inter-galactic medium

• Then
  • Larger boxes: more and more massive galaxies