The intergalactic medium and the epoch of reionization

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Questions?
Gunn-Peterson effect

• In 1965 Gunn and Peterson pointed out that any generally distributed neutral hydrogen would produce a broad depression in the spectrum of high-redshift quasars at wavelengths shortward of 1216 Å.

• The optical depth at the observed frequency $\nu$ for Ly$\alpha$ absorption due to a smoothly distributed “sea” of neutral hydrogen is

$$\tau(\nu) = \int_0^{z_s} \sigma_{\text{Ly}\alpha}[\nu(1 + z)] n_{\text{HI}}(z) \frac{dr_{\text{prop}}}{dz}(z) \, dz$$

• Where $z_s$ denotes the redshift of the background source against which absorption is detected, $\sigma_{\text{Ly}\alpha}$ is the cross-section for Ly$\alpha$ absorption and $n_{\text{HI}}$ is the proper number density of neutral hydrogen atoms.
Gunn-Peterson effect

- For a narrow line, the integral gives (exercise)

\[ \tau(\nu) = 7777 \, h^{-1} \left( \frac{\Omega_b h^2}{0.022} \right) \frac{f_{\text{neut}}(z) \,(1+z)^3}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}. \]

where \( f_{\text{neut}} \) denotes the hydrogen neutral fraction and \( 1+z=\nu_{\text{Ly}\alpha}/\nu \).

The equation applies to all parts of the source spectrum to the blue of the Ly\(\alpha \) emission line. If \( f_{\text{neut}} \sim 1 \) then \( \tau \gg 1 \) at all observable frequencies (i.e. redshifts), and an absorption trough should be detected in the level of the rest frame UV continuum of quasars. This is called the Gunn-Peterson effect. Current upper limits at \( z \approx 5 \) are \( \tau < 0.1 \) and this implies \( f_{\text{neut}}(z = 5) < 4.3 \times 10^{-7} \, h \). Even assuming that 99% of cosmic hydrogen is in the Ly\(\alpha \) forest (or in galaxies), with only 1% in a smoothly distributed component, still \( f_{\text{neut}}(z = 5) < 4.3 \times 10^{-5} \, h \). In summary: since we see the quasar continuum between the discrete absorption lines in a quasar spectrum the smooth component of the IGM must be highly ionized.
Cosmic reionization
also known as the
Epoch of Reionization (EoR)
Introduction

- The existence of the CMB and its blackbody spectrum suggest that the pre-galactic medium (PGM) was hot, fully ionized and tightly coupled with radiation via Thomson scattering off free electrons at redshift \( z > 1100 \)

- At \( z \approx 1100 \), when the PGM temperature dropped below \( 10^4 \) K due to cosmic expansion, protons and electrons combined to form neutral-hydrogen atoms. Photons could then free stream across the universe and form the CMB.

- The absence of Gunn–Peterson troughs in quasar spectra at \( z < 5 \) indicates that the intergalactic medium (IGM) is highly ionized at low redshift

- Can the last two statements be easily conciliated?
FROM THE DARK AGES...
After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

...TO THE RENAISSANCE
The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.
With time sources become more and more abundant. Random points in the IGM start receiving UV photons by more than one source.

Finally, the bubbles cover the whole volume. This is known as percolation (or bubble-overlap) phase.

The first UV sources start ionizing gas in their neighbourhood.
Currently pressing questions

• WHEN: When did it happen? How long did it last?

• WHO: What were the sources responsible?

• HOW: How did it proceed? Was it gradual or sudden? What was its topology? (inside-out vs. outside-in) Was it homogeneous or patchy?
When did reionization take place?

Constraints from quasar absorption lines and CMB
Quasar spectra and absorption lines

3C 273 $z=0.158$

Q1422+2309 $z=3.62$

Courtesy B. Keel
Spectrum of a z~3 quasar
The intergalactic medium

- Lyman-alpha absorption against background quasars can be successfully modeled within CDM models for structure formation.

- The IGM at $z<6$ is highly photoionized by an ultraviolet cosmic background generated by the combined action of young stars and quasars.

- Intergalactic gas appears to have a rather tight temperature-density relation.
Quasar spectra at $z=6$

Becker et al. 2001
Evidence for evolution!
Transmitted flux
Optical depth

Best-fit at $z<5.5$
$$\tau_{gp} \propto (1+z)^{4.3}$$

Best-fit at $z>5.5$
$$\tau_{gp} \propto (1+z)^{10.9}$$

Note that also the scatter grows, as expected near bubble overlap.
GP trough finally seen!

![Graph of GP trough](image)
How the Discovery Was Made

The Normal Hydrogen Absorbers Forest (Reionization Complete)

Ionized Bubbles in a Still Largely Neutral Universe

Opaque Neutral Gas in the Earlier Universe (Before the Reionization)

The Quasar

Line of Sight to the Quasar

The Observed Spectrum:

Intensity

Wavelength or Redshift

Isolated Transmission Spikes Correspond to the Ionized Bubbles Along the Line of Sight

Dark Regions Correspond to the Still Opaque, Neutral Gas Along the Line of Sight
Volume-averaged neutral fraction

The dashed lines show the outcome of two different numerical simulations.
Remarks

• Because of the large optical depth it is hard to push the GP-trough analysis to higher redshifts (e^{-\tau} is basically zero if \(\tau\) is 5 or 5,000 and with the current signal-to-noise of the spectra it is not possible to distinguish the two cases)

• Therefore it is really hard to infer the corresponding neutral fraction (realistically, you can only get a lower limit)!

• The GP results indicate that cosmic hydrogen is likely between 10^{-3.5} to 10^{-0.5} neutral at z=6.

• One expects that transmission is mainly due to rare voids while most HI lies at higher overdensities. In consequence, estimates of the neutral fraction depend on a number of assumptions regarding the density distribution of the baryons, quasar physics, etc.

• Need other methods: e.g. statistics of dark gaps, OI and SiII forest
So, quasar absorption lines suggest that reionization started before $z=6$ and might have reached the percolation phase around $z=6$.

What about CMB studies?
The EoR and the CMB: Temperature anisotropies

- Reionization produces free electrons that can scatter off CMB photons at late times.

- Therefore, CMB probes of the EoR are sensitive to ionized hydrogen and are therefore complementary to the GP effect which is sensitive to neutral hydrogen.

- On scales smaller than the causal horizon at the EoR primordial temperature perturbations are then reduced as $e^{-\tau}$ (with $\tau$ the optical depth to Thomson scattering).

- Patchy reionization, however, generates new temperature fluctuations on small angular scales ($l>2000$)
CMB and reionization

- Rescattering of CMB photons damps fluctuations as $e^{-\tau}$, with $\tau$ the optical depth to Thomson scattering.

- New perturbations are generated on small scales due to the bulk motion of electrons in overdense regions (Ostriker-Vishniac effect).
The EoR and the CMB: Polarization

- In Thomson scattering: scattered radiation is polarized parallel to the incident polarization.

- If, in the rest-frame of the electron, the radiation possesses a non-zero quadrupole anisotropy, then the scattering leads to linear polarization on a scale comparable to the horizon at time of scattering.
A technical issue

- The polarization pattern on the sky can be decomposed into two independent components.
- The E-mode (divergence-like with no-handedness) and the B-mode (curl-like with handedness).
- E-mode generated by reionization.
- B-mode can be generated by gravitational waves and gravitational lensing.

\[
Y_{\ell m, ab}^{(E)} = \frac{1}{\ell (\ell + 1)} \left[ \nabla_a \nabla_b - \frac{1}{2} \delta_{ab} \right] Y_{\ell m}(\hat{\Omega})
\]

\[
Y_{\ell m, ab}^{(B)} = \frac{1}{\ell (\ell + 1)} \frac{1}{2} \left[ \epsilon_{ac} \nabla_c \nabla_b + \nabla_a \epsilon_{bc} \nabla_c \right] Y_{\ell m}(\hat{\Omega})
\]
Temperature fluctuations

Variance at multipole \( l \) (angle \( \sim 180^\circ/l \))

\[ I(l+1)C_l^{TT}/2\pi \text{ [\( \mu K^2 \)]} \]
The WMAP measurement
Re-scattering of CMB photons during and after reionization added to the polarization spectrum at large angular scales.

Nolta et al. 2009
Current results

• The combined analysis of the WMAP 5-yr data (temperature and polarization) gives $\tau = 0.087 \pm 0.017$ (Dunkley et al. 2009)

• This means that nearly 9% of the CMB photons have been re-scattered by free electrons produced by the reionization process.

• Assuming that the universe was reionized instantaneously, this gives $z_{\text{reion}} = 11.0 \pm 1.4$

• This is only an indicative result as reionization is likely to have been extended in time.
How did reionization take place and what were the UV sources?
Still an open question

• It can be easily shown (see for instance the past classes on the intergalactic medium) that at z<4 observed stars and quasars produce enough UV photons to explain the high level of ionization in the IGM

• However, the nature of the sources responsible for converting most of the IGM from neutral to ionized remains uncertain, as does the epoch of reionization
Energetically: easy task!

- Nuclear fusion releases $7 \times 10^6$ eV per proton.
- Black-hole accretion even 10 times more!
- It only takes 13.6 eV to ionize an hydrogen atom.
- Therefore, converting a fraction $\approx 10^{-5}$ of baryonic mass into stars or black holes would be more than enough to ionize the rest of the universe.
Caveats

• Not all the UV photons leak out from galaxies! (This is generally described by the $f_{\text{esc}}$ parameter)

• Ionizing all atoms is not enough, one has also to keep all atoms ionized thus preventing hydrogen to recombine!

• The presence of dense mini-halos can slow down the propagation of ionization fronts.

• Exact estimates depend on many details but, basically, a few ionizing photons per baryon (let’s say from 2 to 10) should be enough to do the job.
Looking for the culprit

• We know that there are not that many bright quasars at z>4. What about galaxies?
• Massive stars in known high-redshift galaxies should produce from 2 to 20 ionizing photons per proton by z=6. This might or not be enough.
• Nuclear fusion also produces metals and one has to pay attention that reionization models do not overproduce the metallicity of the IGM. Many subtle details play a role here, for instance the physical mechanisms with which metals are spread out in the IGM by galaxies.
• The most recent studies indicate that, if galaxies provide a substantial contribution to reionization, then galaxies below current detection limits must play a significant role.
• In other words, steep luminosity functions at the faint end are required.
• Alternatives: mini-quasars, Pop III (metal free) stars, decay of exotic particles (all somewhat unlikely)
Patchy or homogeneous?

• In principle, from the degree of patchiness and the size of the ionizing bubbles before overlap it should be possible to infer the origin of the sources.

• Quasars should produce a very patchy reionization, galaxies a more uniform transition and decaying particles like light neutrinos a very uniform one.

• Current data do not allow this kind of analysis yet but there are ideas about how to do it in the future.
Pop III stars

• Very massive, metal free stars with harder UV spectra

• Boost in ionizing photon rate by a factor of $\approx 20$

• Return to “normal” stellar pops at $Z > 10^{-4} Z_\odot$

• But too few if only one per halo can be formed (remember that molecular hydrogen is destroyed by UV photons)
Numerical simulations

- Numerical simulations including radiative transfer helped shedding new light on the reionization process.

- Note that numerical radiative transfer requires working in 7 dimensions and is very computationally demanding!

- This is much more complex than simulations of the IGM at $z<5$ where the UV background is assumed to be uniform and the optically-thin approximation is used.
Ionization fronts are not spherical

Galaxy at z=7

300 kpc proper
Reionization history and the thermal state of the IGM

- During reionization, the IGM is heated up by the photoionization process.

- For gas around mean density, the dominant cooling process is the adiabatic expansion of the universe, except at $z>7$ when inverse Compton cooling off the CMB is more efficient.

- Because its cooling time is relatively long, the low-density IGM retains some memory of when and how it was ionized.
Constraints from the thermal history of the IGM

- Thermal state at $z<4$ does not remember ionization history at $z>10$

- However, it has short-term memory of $z<10$ events

- An higher reionization redshift implies a lower temperature

- Models cannot match observations?
Helium II reionization
HeII reionization in a nutshell

• The ionization threshold of HeI (24.6 eV) is quite close to that of HI (13.6 eV).

• There is nearly 1 helium atom every 10 hydrogen atoms.

• In the standard picture of reionization, therefore, population II stars ionized the intergalactic HI at \( z > 6 \) as well as the HeI, converting the vast majority of intergalactic helium to HeII.

• However, these stars cannot ionize HeII.

• It is therefore expected that quasars, with their harder UV spectrum, doubly ionize helium at late times (\( z \approx 3 \)).
Simulating HeII reionization

HeII Fraction

0.1

0.5

0.8

0.99

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xHeII log(Trans) T (kilo-K) log $\Gamma$ $\gamma$-heating (kilo-K) (cumulative HeII heating)
HeIII fraction

0.1

0.75

0.90

Beamed quasars

Light-bulbs

Very hard spectrum

$\tau_{\text{IGM \& EoR}} = 10 \text{ Myr}$
HeII Gunn-Peterson effect

There are currently only a handful of HeII Lyα forest sightlines!

Data suggest that second reionization of He has happened around redshift 3 at the peak of quasar activity.

The situation will improve dramatically with the advent of the Cosmic Origins Spectrograph (COS) on HST (installed during the fourth servicing mission in May 2009).
Thermal history at $z \sim 3$

Temperature at mean density and slope of the effective equation of state as a function of redshift. Horizontal errorbars indicate the redshift interval spanned by the absorption lines. Vertical errorbars are $1\sigma$ errors. The continuous line correspond to a simulation with an Haardt-Madau UV background dominated by quasars. The dashed line to a model where quasar provide a much smaller contribution at high redshift. This provides (weak) evidence that HeII reionization happens at $z \sim 3.2$. 
The current state of the art

Fig. 12.— Top Panel: Best-fit power-law index of the $T\cdot \Delta_0$ relation in two simulations (thick curves), as well as its evolution in simulations without a $z \sim 3$ HeII reionization (thin curves). The markers with error bars are measurements of this quantity in the literature, and the references for these measurements are given in the key in the bottom panel. Bottom Panel: Evolution of best-fit $T_0$ in three simulations (thick curves) as well as $\pm 1$ s.d. in this quantity (the thinner curves with the same line style). The thin cyan dot-dashed curves that are increasing with $z$ represent simulations in which HeII reionization occurs at $z > 6$. Also shown are measurements of $T_0$. 
Conclusions

• Understanding hydrogen and helium reionizations is crucial to gain a complete understanding of the IGM and of its evolution.

• Data are still scarce and their interpretation is challenging.

• Uncertainties in the cosmic evolution of UV sources and the need to model radiative transfer makes theoretical models complicated.

• Anyway, the GP effect and CMB data constrain the EoR between $6 < z_{\text{reion}} < 14$.

• The current standard model uses Pop II stars to reionize HI and HeI at $z > 6$ and quasars to reionize HeII at $z \sim 3$. 
The missing baryons and the WHIM

Nicastro et al. 2008

Cen & Ostriker 2006
The introduction of metals into the IGM and subsequent mixing are not understood.
Future perspectives
The Cosmic Origins Spectrograph

- The most sensitive ultraviolet spectrograph ever built for space (10 to 30 times better than STIS)
- Optimized to observe faint point sources
- Installed by spacewalking astronauts on Servicing Mission 4 (May 2009)
- FUV channel: $1150 < \lambda < 1775$ Å
  $R=20,000-24,000$
- NUV channel: $1700 < \lambda < 3200$ Å
  $R=16,000$
- Low-res grism: $1230 < \lambda < 2050$ Å
  $R=2500-3500$
- Cost: 70 M$
COS science

- Charting the cosmic web by studying absorption lines towards background quasars

- Detect the WHIM

- Measure the amount of heavy metals and the history of enrichment

- Constrain the thermal history of the IGM

- Study the HeII Gunn-Peterson trough and HeII reionization
Baryon Oscillation Spectroscopic Survey (BOSS)

- Fall 2009 – Spring 2014
- 1000-fiber spectrograph, $R \approx 2000$, wavelengths: 360-1000 nm
- Spectra of 160,000 quasars at redshifts $2.2 < z < 3$ within $10,000 \, \text{deg}^2$
- Measurement of the angular diameter distance at $z=2.5$ with a precision of 1.5%
- A large database of quasar absorption lines
The Planck satellite

- Medium-Sized Mission (M3) part of ESA’s Cosmic Vision Programme
- Launched on May 14 2009
- Much better sensitivity, angular resolution and frequency range than previous experiments
- The total cost of the Planck mission is about 700 MEUR
Planck will determine the optical depth to reionization with an accuracy of $\Delta \tau = 0.005$.
Prospects with ACT/SPT

Hard to separate the patchy reionization signal from OV+SZ

If this is doable, we could learn about the size of the bubbles
The 21cm background

The key idea is to use CMB backlight to probe 21cm transitions

Brightness temperature at $\lambda = (1+z)$ 21 cm:

$$\delta T_b \approx 23 x_{HI} (1 + \delta) \left( \frac{1 + z}{10} \right)^{1/2} \left( \frac{T_S - T_{cmb}}{T_S} \right) \left( \frac{H(z)}{(1 + z)} \frac{\partial v_r}{\partial r} \right) \text{mK}$$

3-dimensional information: angle on the sky plus wavelength
Hydrogen 21cm radiation

- Spin-flip transition at 1420.4 MHz between hyperfine levels of the 1s state

- Magnetic dipole transition with a probability of $2.9 \times 10^{-15} \text{ s}^{-1}$ (1 transition every $10^7 \text{ yr}$)

- Predicted by van de Hulst 1944, First detected by Ewen and Purcell in 1951
Spin temperature

Ratio of level populations:

\[ \frac{n_1}{n_0} = 3e^{-\Delta E/k_BT_S} = 3e^{-T_\ast/T_S} \]

Coupling mechanisms:

- Radiative transitions (CMB)
- Atomic collisions
- Lyman $\alpha$ pumping

\[ T_S = \frac{T_{CMB} + y_c T_K + y_{Ly\alpha} T_{Ly\alpha}}{1 + y_c + y_{Ly\alpha}} \]
Wouthuysen - Field effect

Selection rules:
$$\Delta F = 0,1 \ (\text{Not } F=0 \rightarrow F=0)$$

$^{2}_1P_{1/2}$

$^{2}_2P_{1/2}$

$^{2}_1P_{1/2}$

$^{2}_0P_{1/2}$

Lyman $\alpha$

Wouthuysen 1952, Field 1958

$T_s \sim T_\alpha \sim T_k$

$W-F \text{ recoils}$

$\lambda \sim 21 \text{ cm}$

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IGM & EoR
Thermal history and 21 cm background

- \( z > 200 \) no signal
- \( 30 < z < 200 \) 21cm detected in absorption against CMB
- \( 20 < z < 30 \) no signal
- \( 6 < z < 20 \) 21cm detected in emission against CMB
Global signal

Shaver 1999
Statistical approach

McQuinn et al. 2006
$\delta T_b$ tomography

Primarily density fluctuations

Early times (z > 15)

Late times (z < 6)

Furlanetto et al. 2004

Ionized regions

5 arcmin
Foreground signal

@ 120 MHz

Jelić & Zaroubi 2006
Foreground: Galactic Synchrotron

Haslam 408 MHz  Much brighter than signal, but no spectral structure

~250 K at 150 MHz
LOFAR in Germany
Pathfinder experiments

• Global signal:
  EDGES (Caltech/MIT),
  CORE (Australia)

• Fluctuations (power spectrum):
  LOFAR (Dutch + EU),
  21CMA (China, formerly called PAST),
  MWA (Australia/MIT),
  GMRT (India, operational),
  PAPER (UC Berkeley)

• Ultimate experiment (tomography):
  SKA (phase-1 2014, full 2020)
James Webb Space Telescope

- 6.6-meter diameter primary mirror, diffraction limited at 2 micron
- Launch planned for 2014, 5-10 years of scientific operations after 6 months of commissioning period
- 5B$ budget (plus European and Canadian contributions)
- The end of the dark ages: first light and reionization is one of the four main science themes of JWST
JWST will mainly tell us about the sources that reionized the universe.

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<td>1.4 nJy at 2 μm</td>
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Cosmic star formation history also from CO lines with ALMA (>2011)
German involvement

- COS: ESA
- BOSS: AIP, MPA, MPIA
- Planck: MPA, DLR
- ACT: MPA
- LOFAR: GLOW (Bochum, Bonn (MPIFR + Uni), Bremen, Garching, Hamburg, Jülich, Köln, Potsdam, Tautenburg)
- ALMA: ESO (regional centre: Bonn, Bochum, Cologne)
- JWST: ESA