Cosmic UV background fluctuations at $z \sim 3$ as traced by metal ions: radiative transfer effects

- Helium reionisation
- UV background at $z \sim 3$
- RT simulation through metals
- UV fluctuations traced by $\eta, T, \frac{\tau_{\text{SiIV}}}{\tau_{\text{CIV}}}$

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Reionisation in the Red Center, Uluru - 14-19.06.2013
He reionisation

- **EPOCH:** He II dominates at $z > 3$ (Reimers 05); an extended reionisation is possible (Bolton 10; Becker 11).
  
  **He fully ionised around $z \sim 2.8$** (Kriss 01; Syphers 11, 11a).

- **He II OPACITY:** highly inhomogeneous (Smette 02; Muzahid 11).

  $$\eta = \frac{N_{\text{He II}}}{N_{\text{HI}}}$$

  varies in [20-200] on [2-10] Mpc/h scales (Fardal 98, Shull 99, Fechner 07)

  $\rightarrow$ Significant spatial fluctuations in the radiation field at the ionisation edges of HI and He II?

- **IGM $T$:** Statistical detections of a jump in $T$ around $z \sim 3$ (Hui & Gnedin 1997; Ricotti et al. 2000; Schaye et al. 2000; Bernardi et al. 2003), but **not** confirmed by independent analyses (McDonald & Miralda-Escudé 2001)
He reionisation: Lyα forest

- $\eta$: in a photo-ionised IGM is proportional to the spectral shape of the ionising background (Miralda-Escude' 73).

\[
\eta \propto \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{HeII}}},
\]

where $\Gamma_{\text{HI}}, \Gamma_{\text{HeII}}$ are photo-ionisation rates of HI and HeII.

→ Spatially fluctuating spectral shape?

- $T$: equation of state of photo-ionised medium follows (Hui&Gnedin 97; Valageas et al. 02):

\[
T = T_0 \Delta^{\gamma - 1},
\]

where $T_0$ is temperature at mean density and $\Delta$ is the gas overdensity. → Fluctuations in $\gamma$?
UV background modelling at z~3

- UVB uncertain at z~3: F. Haardt and P. Madau assume spatially uniform UVB and model it with 1D code (CUBA).

- For photons E>1Ryd (13.6 eV) the HM assumption can fail at z~3:

  1) **POINT SOURCE VARIABILITY:**
     - QSOs are rare in space + clustering
     - Finite lifetime
     - Spectral variability
       → HeII reionization is completed by QSOs at z~3?

  2) **RADIATIVE TRANSFER EFFECTS:** could affect small and large scales
     - Small scale (~10h^{-1} Mpc) RT effects (Maselli&Ferrara 05)
     - Large scale: filtering but.. collisionally ionised gas could produce $N_{\text{HeII}}/N_{\text{HI}} < 10$.

SPATIAL FLUCTUATIONS OF THE UVB INTENSITY AND SPECTRAL SHAPE ARE TRACED H, He..

→ CAN WE USE METAL IONS ??
UV Spectral Shape Modelling

- A plethora of potentials near $E=4\text{Ryd}$ (54.4 eV).
- Metals ions can provide additional points across the HeII absorption to fix the slope and check/invalidate the model assumptions.

Oppenheimer, et al., 2009:

Metal ionization fractions calculated with CLOUDY (Ferland et al.) as function of density and temperature.

NOT SELF-CONSISTENT WITH THE RT: tables assume the spectral shape slope!
Spectral Shape Modelling $\zeta_{\text{obs}} : \tau_{\text{CIV}} / \tau_{\text{SiIV}}$

MAYBE OBSERVATIONS CAN HELP...

- **Songaila (1998):** YES. Abrupt change of $\tau_{\text{SiIV}} / \tau_{\text{CIV}}$ around $z \sim 3$ → sudden hardening of the UVB.

- **Agafonova (2005-2007):** YES. UVB Spectral shape shows a sharp reduction in flux in the energy range $3 \text{ Ryd} < E < 4 \text{ Ryd}$ → sudden hardening of the UVB. Metal ions can be used.

- **Kim et al. (2002):** NO. Do not see any abrupt change in $N_{\text{SiIV}} / N_{\text{C IV}}$ at $1.6 < z < 3.6$. → Local sources dominated metals. Not a good tracer.

- **Boksenberg (2003):** NO

- **Aguirre (2004):** NO

Conclusions dependent on photoionisation models. RT neglected
Simulation: small scale fluctuations induced by RT

**HYDRO SETUP:**
- **Hydro Snapshot** at z~3 (Gadget3): metal enrichment and spreading accounted for (Maio 2010). Scale: 10/h Mpc.
- 11 metals (Tornatore 2007). We consider only C, O, Si. Other metals can be added.
- HM96 UVB model.

**RT SETUP:**
- CRASH in post-processing.
- Photo-ionised metals. Collisionally ionised regions accounted for separately.
- Spatially homogeneous HM96 UVB.
- C, O, Si ions evaluated including cooling by metal lines.

**IC:**
- In absence of a full reionisation setting the initial ionisation, it starts from neutral gas at T~100K.
- Follows the RT as in Maselli and Ferrara 2005.

**AIM:**
- Amplitude of spatial fluctuations in:
  \[ \eta = \eta(\Delta) \]
  \[ T = T(\Delta) \]
  \[ \zeta = \zeta(\Delta) \]
  
  induced by the RT through the cosmic web at z~3.
- Theoretically confirms that the metal line ratios can be used as tool.
Fluctuations in $\eta$

- Calculated as in Fardal 98:

$$\eta \sim \frac{\alpha_{\text{HeII}}(T)}{\alpha_{\text{HII}}(T)} \frac{n_{\text{HeIII}}}{n_{\text{HII}}} \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{HeII}}}.$$ 

- Shows evident spatial correlation $\eta(\Delta)$

Slice cut at $t \sim 5.5 \times 10^6$ yrs. $\Delta \sim 1$ white solid line, $\Delta \sim 5$ black dashed, $\Delta \sim 10$ black solid.

- $\langle \eta \rangle \sim 277$ at $z \sim 3$
- $210 < \eta < 285$ in 80% volume, $\delta \rho/\langle \rho \rangle \sim 10$-$20\%$ fluctuations.
- $\delta \rho/\langle \rho \rangle$ up to 60% in 20% volume.

Scatter plot of $\eta(\Delta)$ at $t \sim 5.5 \times 10^6$ yrs. The average value of $\eta(\Delta)$ in red crosses.
Fluctuations in $T$

- Calculated self-consistently with H, He, metal cooling.
- Evident spatial correlation $T(\Delta)$
- Metal cooling efficient in few percent of volume ($Z > 0.5Z_{\text{Sol}}$) introduces scatter.

Scatter plot of $T(\Delta)$ at $t \sim 5.5 \times 10^6$ yrs.  $\langle T(\Delta) \rangle$ in red crosses.

$\Delta \sim 0.5$ cyan solid line, $\Delta \sim 1$ white solid line, $\Delta \sim 5$ black dashed, $\Delta \sim 10$ black solid

- $\langle T \rangle \sim 3.2 \times 10^4 [K]$ at $z \sim 3$
- $\delta T/\langle T \rangle \sim 10\%$ in $\Delta < 1$.
- $\delta T/\langle T \rangle$ up to 40\% in $\Delta > 1$. 
Fluctuations in $\zeta_{\text{obs}}$

- Calculated in photo-ionisation equilibrium as:

$$\zeta_{\text{obs}} \equiv \frac{\tau_{\text{SiIV}}}{\tau_{\text{CIV}}} \sim \frac{\sigma_{\text{SiIV}} n_{\text{Si}} x_{\text{SiIV}}}{\sigma_{\text{CIV}} n_{\text{C}} x_{\text{CIV}}} \sim 1.7 \frac{x_{\text{SiIV}}}{x_{\text{CIV}}} 10^{[\text{SiIV/CIV}] - 0.77}$$

- Sensitive both to spectral shape and $[\text{SiIV/CIV}]$.

Scatter plot of $x_{\text{CIV}} / x_{\text{SiIV}}(\Delta) \sim \zeta^{-1}$ at $t \sim 5.5 \times 10^6$ yrs.

Scatter plot of $[\text{Si/C}]$. 
- $0.001 - 0.01$ red points.
- $0.01 - 0.1$ green.
- $0.1 - 0.5$ blue.
- $0.5 - 1$ pink.

- $<[\text{Si/C}]> \sim 0.77$ at $z \sim 3$ (see Aguirre 04)
- $0.4 < [\text{Si/C}] < 0.8$ in $0.1 < \Delta < 10$. It scatters with the gas metallicity $Z$.

- $\zeta^{-1}$ increases with $\Delta$: $8 \rightarrow 48$
- $\zeta^{-1}$ shows a scatter from 20 to 40% only around $\zeta^{-1} \sim 8$. 

Scatter plot of $[Z/Z_\odot]$. 
- $0.001 \leq Z/Z_\odot \leq 0.01$
- $0.01 \leq Z/Z_\odot \leq 0.1$
- $0.1 \leq Z/Z_\odot \leq 0.5$
- $0.5 \leq Z/Z_\odot \leq 1$
- $Z/Z_\odot \geq 1$
Fluctuations in $\zeta_{\text{obs}}$

- Clear decreasing trend with $\Delta$
- Scatter increases from 25% up to 50% at $\Delta \sim 10$.
- Associated with metallicity: $0.1 < Z/Z_{\odot} < 0.5$

Scatterplot of $\zeta_{\text{obs}}$ at $t \sim 5.5 \times 10^6$ yrs. Colours indicate the metallicity of the systems as in legend.

- Under-dense regions statistically irrelevant.
- Fluctuations of $\zeta_{\text{obs}}$ up to 40% in less than 0.15% volume.
- Fluctuations $\sim 15\%$ in $\sim 3\%$ volume.
Why ?

- The shaping is a function of $\Delta$. It is well traced by fluctuations of $\eta$ and $T$.

- CRASH is sensitive to fluctuations of metal ions ($\zeta^{-1}$) derived from the UVB shaping.

- Metal enriched domain in which $Z > 0.1Z_{\text{sol}}$ reduced to 7% of total.

- Mechanical Feedback de-correlates $Z-\Delta$ reducing the available volume in which shaping is relevant.

- Fluctuations of $\zeta_{\text{obs}}$ up to 40% in less than 0.15% volume.

- Fluctuations $\sim 15\%$ in $\sim 3\%$ volume.
Conclusions

- RT induces fluctuations up to 40% in \( \eta \) and T.
- RT induces also fluctuations in metal component tracked by \( \zeta_{\text{obs}} \) but visible in few % of volume.

but.....

- Other metal tracers to investigate: OVI.
- Effects galaxy variability in small scales: dominate the ionisation of metals or induce fluctuations?
- Is the large scale background produced by QSOs homogeneous? Does it fluctuate? How is this affecting the small scales?
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THANK YOU