GRBs as reionization probes

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Talk Plan

⋆ GRBs as a reionization probe: strength and weakness
  ⋆ the case of GRB 050904 and some other GRBs

⋆ some stories about GRB 130606A @ z=5.9
  ⋆ extremely high-S/N spectra taken, high precision analysis for reionization possible
  ⋆ controversy between Gemini/Subaru/VLT?

⋆ On the effect of Lyα cross section formulae (as a function of wavelength) adopted

⋆ Future?
  ⋆ prospects of 30m-class telescopes
  ⋆ simulating GRB spectra in cosmological reionization simulation
Cosmic Reionization

- The Universe (hydrogen) became neutral at z~1100
  - the cosmic recombination

- Hydrogen in IGM today is highly ionized
  - the Gunn-Peterson Test

- The universe must have been reionized at around z~10
  - most likely by UV photons by first stars
  - when? how? important benchmark to understand galaxy formation
The Gunn-Peterson Test

- Lyα absorption features of QSOs indicating that IGM neutral fraction rapidly increasing to \( z \sim 6 \)
  - close to reionization?

- but saturated GP troughs only gives a lower limit of \( n_{\text{HI}}/n_{\text{H}} > 10^{-3} \)

White+’03

Fan+’05
Observational Constraints on Reionization History

- Lyα Galaxy, GRB & GP Trough length
- Stromgren Sphere
- Gunn-Peterson
- Late WMAP
- Double
- Early

* Fan+ ‘06
Observational Constraints on Reionization History

Planck’13: $z_{re} = 11.4_{-2.8}^{+4.0}$

\[ \chi_{HI} \]

Redshift

\[ 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \]

\[ \times 10^{-4} \quad \times 10^{-3} \quad \times 10^{-2} \quad 0.1 \quad 1.0 \]

GRB 140515A

ULAS J1120+0641

Gunn–Peterson effect

\[ \hat{\star} \text{Chornock+’14} \]
GRB as a Reionization Probe

- **Strengths:**
  - GRBs detectable at $z \gg 6$
  - Probes more normal (less biased) region in the universe than quasars
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - Simple power-law spectrum
  - Damping wing analysis to precisely measure $x_{HI} = n_{HI}/n_H$

**Diagram:**
- GP trough $\rightarrow x_{HI} > 10^{-3}$
- Damping wing $\rightarrow$ measure $x_{HI}$

GRB 050904@z=6.3, TT+ '06
GRB as a Reionization Probe (2)

- Weakness:
  - Degeneracy between damped Lyα (DLA) of host galaxies and IGM damping wing
    - can be broken by:
      - metal absorption lines
      - Lyβ feature
    - \( x_{HI} < 0.17 \) (68\%C.L) or 0.6 (95\%C.L.) by fitting to GRB 050904 (dominated by host HI)
  - we need low \( N_{HI} \) host galaxy to measure \( x_{HI} \) accurately
  - event rate not so high
    - only several GRBs at \( z > 6 \) from 2005

IGM DW
\( z=6.36 \)
\( x_{HI}=1.0 \)

DLA DW
\( z=6.295 \)
\( \log N_{HI}=21.62 \)

GRB 050904@\( z=6.3 \), TT+ ‘06
GRB 080913 @ z~6.7

(Greiner+’09)
2-3 hrs, z’~24.5(AB), 2400 s exp.
damping wing detected, but difficult to
discriminate DLA or IGM
c.f. GRB 050904, z~6.3
3.4 days, z’=23.7(AB), 4 hr exp.
GRB 090423 @ z~8.2

Salvaterra+’09

Tanvir+’09, ~20 hr, J~20.8
Only upper bound on $N_{HI}$ (=no detection of damping wing)
The best opportunity ever: GRB 130606A

- exceptionally bright afterglow
- ultra-high S/N spectra taken by Gemini, GTC, Magellan, Subaru, VLT, ...
- host HI at most log(N_{HI}) < 19.8, good for IGM study!
- c.f. 21.6 for GRB 050904

Chornock+’13
Gemini vs. Subaru vs. VLT

  - no evidence for IGM HI by damping wing analysis
  - $f_{\text{HI}} < 0.11$ (2 $\sigma$)
  - spectral index $\beta = -1.99$ ($f_\nu \propto \nu^\beta$), very different from $\beta \sim -1$ found by more recent studies

- Totani et al. 2014 (Subaru, PASJ, 66, 63)
  - $\sim 3 \sigma$ preference for IGM HI, with
    - $f_{\text{HI}} \sim 0.09$ if $z_{\text{IGM, u}} = z_{\text{GRB}} = 5.913$ ($\beta = -0.93$)

- Hartoog et al. 2015 (VLT, A&A 580, 139)
  - $\beta = -1.02$ from optical-NIR spectrum
  - no evidence for IGM HI, $f_{\text{HI}} < 0.03$ (3 $\sigma$)
Damping Wing Analysis for Subaru Data

- Subaru/FOCAS spectrum in 10.4-13.2 hr after the burst
- S/N=100 per pixel (0.74A)!
- 8400-8900 A which is the most sensitive to IGM HI signature
- strong absorption regions excluded from analysis
Fitting Residuals

- power-law + host HI only
  - free parameters: power-law index, \( N_{\text{HI}} \), \( \sigma_v \)
  - showing curved systematic residual
  - amplitude \( \sim 0.6\% \) of continuum flux

- diffuse IGM HI can reduce the residual by about 3 sigma statistics
  - IGM extending to \( z_u = z_{\text{GRB}} = 5.913 \), with \( f_{\text{HI}} \sim 0.1 \)
  - IGM extending to \( z_u \sim 5.8 \), with \( f_{\text{HI}} \sim 0.4 \)
    - corresponding to dark GP troughs to this sightline

TT+’14
DW from various components

- wavelength close to Ly $\alpha$ center is dominated by HI in the host galaxy

- IGM HI becomes relatively important at wavelength far from Ly $\alpha$

- wavelength range choice is a crucial issue in the damping wing analysis for reionization!
Very subtle! systematics?

- various sources of systematics examined, but unlikely to explain the 0.6% curvature in the narrow range of 8400-8900 A
  - spectrum reduction, calibration
    - calibration accuracy is < 0.2%
    - no known systematics can explain the observed curvature
  - extinction at host
    - extinction does not explain the strong curvature in the short wavelength range
  - DLAs on the sightline
    - disfavored from Lyβ and metal absorption
what’s the origin of Subaru/VLT controversy?

- To reveal this, the Subaru and VLT spectra have been exchanged by the two teams
  - I thank the VLT team for kindly agreeing with this exchange

- VLT spectrum averaged on the Subaru spectrum grids
  - VLT has a better spectral resolution
  - S/N similar per wavelength

- no systematic trend on > 100 Å scale

- how about adopting the same Subaru analysis code on the VLT spectrum?
Result of TT’s-code on VLT spectrum. 1

<table>
<thead>
<tr>
<th>model</th>
<th>$\log(N_{H_1}^{\text{host}})$</th>
<th>$\sigma_v$ (km/s)</th>
<th>IGM $f_{H_1}$</th>
<th>$\chi^2$</th>
<th>$\Delta\chi^{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>fit to the Subaru spectrum</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>host H\textsubscript{} I only</td>
<td>19.877\textsuperscript{+0.008}\textsubscript{-0.015}</td>
<td>0.0\textsuperscript{+89.9}\textsubscript{-0.0}</td>
<td>fixed to zero</td>
<td>95.10</td>
<td>14.48</td>
</tr>
<tr>
<td>host+IGM H\textsubscript{} I</td>
<td>19.768\textsuperscript{-0.032}</td>
<td>62.0\textsuperscript{+38.0}\textsubscript{-62.0}</td>
<td>0.061\textsuperscript{+0.007}\textsubscript{-0.007}</td>
<td>80.62</td>
<td>-</td>
</tr>
<tr>
<td><strong>fit to the VLT spectrum</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>host H\textsubscript{} I only</td>
<td>19.806\textsuperscript{+0.014}\textsubscript{-0.016}</td>
<td>0.0\textsuperscript{+52.0}\textsubscript{-0.0}</td>
<td>fixed to zero</td>
<td>292.57</td>
<td>11.89</td>
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<tr>
<td>host+IGM H\textsubscript{} I</td>
<td>19.621\textsuperscript{+0.059}\textsubscript{-0.057}</td>
<td>0.0\textsuperscript{+100.0}\textsuperscript{-0.0}</td>
<td>0.087\textsuperscript{+0.017}\textsubscript{-0.029}</td>
<td>280.68</td>
<td>-</td>
</tr>
</tbody>
</table>

- $\beta$ fixed at $-1.02$ as measured by VLT
- IGM HI extends to $z_{\text{GRB},u} = z_{\text{GRB}} = 5.913$
- The original Subaru result ($\sim3\sigma$ preference for IGM HI) confirmed using VLT spectrum
the same trend for the fit residuals by no IGM HI model
What’s the origin of discrepancy?

- Wavelength ranges used are very different for Subaru and VLT papers
  - 8406-8462 Å by VLT
  - 8426-8900 Å by Subaru (<8426 Å avoided because of strong dependence on host HI velocity distribution)
- When the TT’s code adopted on the VLT spectrum, I confirmed the VLT paper result (no evidence for host HI)
- The VLT-paper range is highly sensitive to velocity distribution of HI in the host
  - $\sigma_v = 61.8\pm3.3$ km/s by our fit result
  - Systematics about unknown realistic velocity distribution is a worry
On the Ly $\alpha$ cross section formulae

- classical Rayleigh scattering
  \[
  \sigma_R(\omega) = \sigma_T \frac{f_{12}^2 \omega^4}{(\omega_0^2 - \omega^2)^2 + \Gamma_{2p}^2 \omega^2},
  \]

- Lorentzian
  \[
  \sigma_L(\omega) = \sigma_T \left( \frac{f_{12}}{2} \right)^2 \frac{\omega_0^2}{(\omega_0 - \omega)^2 + \Gamma_{2p}^2 / 4}
  \]

- Peebles’ two-level approximation
  \[
  \sigma_P(\omega) = \frac{3 \lambda_0^2}{8\pi} \frac{\Gamma_{2p}^2 (\omega/\omega_0)^4}{(\omega_0 - \omega)^2 + \Gamma_{2p}^2 (\omega/\omega_0)^6 / 4}.
  \]

- second order perturbation theory for fully quantum mechanical scattering (Bach+’14)
  \[
  \sigma(\omega) = \sigma_L \frac{4 (\omega/\omega_0)^4}{(1 + \omega/\omega_0)^2} [1 + f(\omega)].
  \]

\[
  f(\omega) = a \left( 1 - e^{-bx} \right) + cx + dx^2
  \]

\[
  \begin{aligned}
  a &= 0.376 \\
  b &= 7.666 \\
  c &= 1.922 \\
  d &= -1.036,
  \end{aligned}
\]
effect on HI opacity by Ly α cross section formulae

- ~10% difference in cross section / HI opacity
- The Peebles’ formulae often used shows the largest deviation from BL (Bach-Lee) formula
- How much is the effect on the damping wing fitting results?
  - perhaps the evidence for IGM HI reported by TT+’14 just an artifact by using inaccurate cross section formula?
Fitting results dependence on cross section formulae

- on the Subaru data of the GRB 130606A spectrum
- with the fitting method of TT+’14, only changing Ly $\alpha$ cross section formula
- preference to IGM HI by $\sim3$-4 $\sigma$ unchanged

<table>
<thead>
<tr>
<th>cross section formula</th>
<th>$\lg(N_{HI}^{host})$</th>
<th>$\sigma_v$ (km/s)</th>
<th>IGM $f_{HI}$</th>
<th>$\chi^2$</th>
<th>$\Delta\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>host H I only model</td>
<td></td>
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</tr>
<tr>
<td>Lorentzian</td>
<td>19.869$^{+0.010}_{-0.010}$</td>
<td>0.0$^{+70.2}_{-0.0}$</td>
<td>fixed to zero</td>
<td>91.81</td>
<td>10.74</td>
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<tr>
<td>Rayleigh</td>
<td>19.875$^{+0.010}_{-0.008}$</td>
<td>22.1$^{+63.1}_{-22.1}$</td>
<td>fixed to zero</td>
<td>94.21</td>
<td>13.50</td>
</tr>
<tr>
<td>Peebles</td>
<td>19.877$^{+0.015}_{-0.009}$</td>
<td>0.0$^{+89.9}_{-0.0}$</td>
<td>fixed to zero</td>
<td>95.10</td>
<td>14.48</td>
</tr>
<tr>
<td>Bach &amp; Lee</td>
<td>19.866$^{+0.009}_{-0.009}$</td>
<td>0.0$^{+63.5}_{-0.0}$</td>
<td>fixed to zero</td>
<td>90.66</td>
<td>9.88</td>
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<tr>
<td></td>
<td>host + IGM HI model</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Lorentzian</td>
<td>19.755$^{+0.033}_{-0.033}$</td>
<td>100.0$^{+0.0}_{-100.0}$</td>
<td>0.057$^{+0.0012}_{-0.007}$</td>
<td>81.07</td>
<td>-</td>
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<tr>
<td>Rayleigh</td>
<td>19.765$^{+0.033}_{-0.032}$</td>
<td>54.6$^{+45.4}_{-54.6}$</td>
<td>0.060$^{+0.008}_{-0.007}$</td>
<td>80.71</td>
<td>-</td>
</tr>
<tr>
<td>Peebles</td>
<td>19.768$^{+0.032}_{-0.029}$</td>
<td>62.0$^{+38.0}_{-62.0}$</td>
<td>0.061$^{+0.007}_{-0.011}$</td>
<td>80.62</td>
<td>-</td>
</tr>
<tr>
<td>Bach &amp; Lee</td>
<td>19.751$^{+0.029}_{-0.029}$</td>
<td>100.0$^{+0.0}_{-100.0}$</td>
<td>0.056$^{+0.006}_{-0.006}$</td>
<td>80.78</td>
<td>-</td>
</tr>
</tbody>
</table>
What do we need to increase the rate of GRBs useful for reionization?

- GRB rate study indicate that >1% of GRBs are at z>6
  - e.g. Elliott+’12

- Current 8m telescopes are not sufficient to measure the damping wing for typical GRB luminosities
  - GRB 050904/130606A was exceptionally bright!

- We need more sensitive NIR spectrograph
  - 30m-class telescopes / JWST
30m/JWST
30m telescope sensitivity vs. GRBs

- convert into R mag, $z=1$
- $F_\nu \propto t^{-1} \nu^{-1}$
- observe at 1 day after $z=10$
  burst $\rightarrow \sim 0.1$ day for $z=1$

(original figure from Greiner+’09)
simulating GRB spectra with reionization simulation

- ongoing work by Ryota Baba, TT, Naoki Yoshida, and Hyunbae Park
- calculating “real” Ly $\alpha$ damping wing in inhomogeneous density and ionization degree
- how would it be observed by “model fitting” assuming homogeneous IGM?
- relation between mean $f_{\text{HI}}$ in simulation vs. $f_{\text{HI}}$ distribution from fits to GRBs?

reionization simulation by Park+’13

contour: density $\times$ ionization fraction
simulating GRB spectra with reionization simulation

- density and ionization degree along a path in the simulation
Conclusions

- GRBs are a unique probe of reionization
  - less biased than quasars
  - damping wing on pure power-law spectrum, avoiding GP through saturation

- high precision damping wing analysis indeed possible (e.g. GRB 130606A)
  - but systematics must be carefully treated

- strong constraints on reionization history hampered by low event rate of high-z and bright GRB afterglows

- future 30m class telescopes will change the status