GRBs as reionization probes

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Talk Plan

• concentrate on “Ly $\alpha$ damping wing fitting analysis” to get constraints on IGM neutral fraction

• review on GRBs as a reionization probe: the status before GRB 130606A

• On the results from GRB 130606A @ $z=5.9$
  • the best opportunity ever for reionization study by GRBs
  • controversy between Gemini/Subaru/VLT? what’s the origin?

• On the effect of Ly $\alpha$ cross section formulae (as a function of wavelength) adopted
  • need to be careful in the “high precision GRB cosmology era”
Cosmic Reionization

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

- 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

Djorgovski+
The Gunn-Peterson Test

- Lyα absorption features of QSOs indicating that IGM neutral fraction rapidly increasing to $z \approx 6$
  - 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

- Fan+ ’06
A Next Step: Using Ly $\alpha$ Red Damping Wing

- measurement of $f_{\text{HI}}=n_{\text{HI}}/n_{\text{H}}$, rather than lower limit, is possible if damping wing feature by neutral IGM is detected!

- GRBs especially powerful:
  - simple power-law unlike quasars
  - no proximity effect
  - more normal regions than quasars

- Obstacles:
  - low event rate of high-z GRBs
  - contamination by HI in host galaxies

- GRB 050904: the first meaningful constraint
  - 95% C.L. upper limit $f_{\text{HI}} < 0.6$ (TT +’06)

GRB 050904@z=6.3, TT+ ‘06
Observational Constraints on Reionization History

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

• Chornock+ ’14
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 $z_{\text{IGM},u} = z_{\text{GRB}} = 5.913$ ($\beta = -0.93$)
    - $f_{\text{HI}} \sim 0.4$ if $z_{\text{IGM},u} = 5.83 < 5.913$ ($\beta = -0.74$) ← now disfavored from VLT measurement of $\beta$

  - $\beta = -1.02$ 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 (0.74Å)!
- 8400-8900 Å which is the most sensitive to IGM HI signature
- avoid strong absorption
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
  - \( f_{\text{HI}} \sim 0.1 \), if IGM extending to \( z_u = z_{\text{GRB}} = 5.913 \)

\[ \text{TT+’14} \]
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 Å
  - 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>$\lg(N_{H_1}^{\text{host}})$</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>fit to the Subaru spectrum</td>
<td></td>
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</tr>
<tr>
<td>host H I only</td>
<td>$19.877^{+0.008}_{-0.015}$</td>
<td>$0.0^{+89.9}_{-9.9}$</td>
<td>fixed to zero</td>
<td>95.10</td>
<td>14.48</td>
</tr>
<tr>
<td>host+IGM H I</td>
<td>$19.768^{+0.032}_{-0.032}$</td>
<td>$62.0^{+38.0}_{-62.0}$</td>
<td>0.061$^{+0.007}_{-0.007}$</td>
<td>80.62</td>
<td>-</td>
</tr>
<tr>
<td>fit to the VLT spectrum</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>host H I only</td>
<td>$19.806^{+0.014}_{-0.016}$</td>
<td>$0.0^{+52.0}_{-0.0}$</td>
<td>fixed to zero</td>
<td>292.57</td>
<td>11.89</td>
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<tr>
<td>host+IGM H I</td>
<td>$19.621^{+0.059}_{-0.057}$</td>
<td>$0.0^{+100.0}_{-0.0}$</td>
<td>0.087$^{+0.017}_{-0.029}$</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 (~3 $\sigma$ preference for IGM HI) confirmed using VLT spectrum
Result of Subaru-code on VLT spectrum. 2

- 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 (<8426Å 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

![Graph showing wavelength range](image)
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)

\[ \sigma(\omega) = \sigma_L \frac{4 (\omega/\omega_0)^4}{(1 + \omega/\omega_0)^2} \left[ 1 + f(\omega) \right]. \]

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

\[ \begin{align*}
    a &= 0.376 \\
    b &= 7.666 \\
    c &= 1.922 \\
    d &= -1.036,
\end{align*} \]
• ~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 $\sim$3-4 $\sigma$ unchanged

| cross section formula | $\log(N_{H_1}^{\text{host}})$ | $\sigma_v$ (km/s) | IGM $f_{HI}$ | $\chi^2$ | $\Delta\chi^2$
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<tbody>
<tr>
<td>host HI only model</td>
<td></td>
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<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>
</tr>
<tr>
<td>host + IGM HI model</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>
</tr>
<tr>
<td>Rayleigh</td>
<td>19.765 $^{+0.033}_{-0.033}$</td>
<td>54.6 $^{+45.4}_{-54.6}$</td>
<td>0.060 $^{+0.008}_{-0.007}$</td>
<td>80.71</td>
<td>-</td>
</tr>
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<td>Peebles</td>
<td>19.768 $^{+0.032}_{-0.032}$</td>
<td>62.0 $^{+38.0}_{-62.0}$</td>
<td>0.061 $^{+0.007}_{-0.007}$</td>
<td>80.62</td>
<td>-</td>
</tr>
<tr>
<td>Bach &amp; Lee</td>
<td>19.751 $^{+0.020}_{-0.029}$</td>
<td>100.0 $^{+0.0}_{-100.0}$</td>
<td>0.056 $^{+0.011}_{-0.006}$</td>
<td>80.78</td>
<td>-</td>
</tr>
</tbody>
</table>
Conclusions (1/2)

- GRB 130606A gives the best ever opportunity to probe reionization by GRBs

- ~3σ evidence for IGM HI is found by the damping wing analysis of Subaru spectrum
  - $f_{\text{HI}} \sim 0.1$ if $z_{\text{IGM,u}} = z_{\text{GRB}} = 5.913$
  - robust against known systematics (spectrum, extinction, intervening DLA)
  - the first evidence for intervening HI to GRB sightlines
  - suggesting that the reionization not yet complete at z~6, but needs more sightlines to examine inhomogeneity

- discrepant result from VLT (Haartoog et al. 2014)?
  - data consistent with each other, and the same result confirmed when the same analysis is done on the two different spectra
  - high precision damping wing analysis indeed possible!
  - discrepancy comes from different wavelength ranges
  - need to be careful for systematics in analysis methods!
  - systematics about host HI velocity distribution seems serious when using range close to Lyα resonance
Conclusions (2/2)

- Now we are in the era of “GRBs as a high precision reionization probe”
  - sensitive to $f_{HI} \sim 0.1$ at $z \sim 6$!
  - systematics must be carefully treated

- Choice of Ly $\alpha$ cross section formulae is important in a high-precision analysis such as GRB 130606A
  - but preference to IGM HI reported by TT+'14 unchanged

- current limitation of GRBs as a reionization probe:
  - low event rate of sufficiently bright GRBs at $z \sim 6$
  - this situation will be improved by 30m-class telescopes
  - future GRB missions in synergy with 30m-class telescopes will be crucial
  - good data for many GRBs would reveal not only the mean but also inhomogeneity of reionization history