Gamma-Ray Bursts as Cosmological Probes

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Talk Plan

- GRB as a probe of cosmic star formation history
- GRB as a probe of cosmic reionization
- GRB as a standard candle to study cosmic expansion
- GRB as a probe of cosmic optical/infrared background radiation

- “cosmology” including galaxy formation, high-z universe, in addition to “core” cosmology (cosmological parameters, dark energy, etc.)
GRBs as a Probe of Cosmic Star Formation History

- We expect GRB rate $\propto$ SFR, making it a SFR indicator (Totani ’97; Wijers+’08)

- strength:
  - reaches to very high-redshift
  - no extinction by dust (for gamma-rays)
  - no limit about host galaxy luminosity

- weakness:
  - complicated efficiency for detection and redshift measurements
  - may be a biased SF indicator
    - e.g., metallicity / host galaxy mass
    - can be a probe of GRB progenitor nature, if CSFH is given

Kneiske+’10
GRB rate history different from CSFH?

- various papers found that (long) GRB rate is relatively higher than SFR at high-z
  - $\text{RGRB/SFR} \propto (1+z)^\alpha$, $\alpha \sim 1$
  - e.g., Daigne+’06; Guetta+’07; Le+’07; Salvaterra+’07; Kistler+’08,’09; Li ‘08; Salvaterra+’09; Campisi+’10; Qin+’10; Wanderman+’10

- indicating low metallicity for GRBs?
- some other selection effects?

Butler+’10
Sampling Bias of GRB redshifts

- recent more complete sample indicates that the primary reason of no-afterglow GRBs (“dark GRBs”) is large extinction by dust
  - Greiner+’10; Kruhler+’10
  - no low-Z preference?
  - Z dispersion within a host? (Niino ’11, see also poster #41

- the past sample with known redshifts is most likely biased to low-mass, low-metallicity galaxies

- the latest sample by GROND is consistent with the simple picture of $R_{\text{GRB}} \propto \text{SFR}$
  - Elliott+’12

- secure conclusion: LGRB rate is roughly consistent with simple relation of $R_{\text{GRB}} \propto \text{SFR}$
  - sampling bias is the crucial issue to derive stronger conclusions from GRB rate study

Hashimoto+’10
short GRBs vs. CSFH

- In the NS-NS(BH) merger scenario, delay time distribution (DTD) of GRB events from star formation should be $\propto t_D^{-1}$
  - $t_{GW} \propto a^4$ (a: initial binary separation)
  - only weakly depends on separation distribution (TT ’97)

- Is SGRB rate history consistent with CSFH convolved with DTD?
  - an interesting study if we have enough number of SGRBs with $z$

- A similar study: type Ia SN rate
  - rate studies now converges to SN Ia DTD of $t_D^{-1}$ (TT+’08; ...)
  - preferring double-degenerate (WD-WD) progenitor scenario
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 Reionization Probes

- quasar Gunn-Peterson test:
  - gives only lower limit at $z > 6$
  - proximity effect

- Cosmic microwave background polarization:
  - only integrated information over $z$

- Lyα emitter luminosity function:
  - highly model dependent

Fan+’06
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 $x_{\text{HI}} (=n_{\text{HI}}/n_{\text{H}})$
  - Damping wing
  - $x_{\text{HI}} > 10^{-3}$
  - GP trough

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

**Weakness:**

- Degeneracy between damped Ly $\alpha$ (DLA) of host galaxies and IGM damping wing
  - can be broken by metal absorption lines
  - we need low $N_{HI}$ host galaxy to measure $x_{HI}$ accurately

- Event rate not so high
  - GRB 050904 is still the only one useful constraint on reionization by GRBs since 2005!
  - $x_{HI} < 0.17$ (68% C.L.) or 0.6 (95% C.L.) by fitting

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**Parameters:**

- **DLA DW**
  - $z = 6.295$
  - $\log N_{HI} = 21.62$

- **IGM DW**
  - $z = 6.36$
  - $x_{HI} = 1.0$

**GRB 050904**

@ $z = 6.3$, TT+ ‘06
GRB 080913 @ z~6.7

\[
\begin{align*}
\log N_{\text{HI}} &= 0.0, \ x_{\text{HI}}=1.0 \ z=6.710 \\
\log N_{\text{HI}} &= 21.0, \ x_{\text{HI}}=0.0 \ z=6.692
\end{align*}
\]

(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 \( N_{\text{HI}} \) (=no detection of damping wing)
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 was exceptionally bright!

- We need more sensitive NIR spectrograph
  - LGS-AO by 8m telescopes
  - 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)
remarks on reionization study by GRBs

- The number of reionization-constraining GRBs still very limited by
  - insufficient sensitivity of NIR spectroscopy
  - needs of low $N_{\text{HI}}$ host galaxy

- NIR spectroscopic sensitivity will greatly improve in the near future

- Even a few measurements of IGM neutral fraction by GRBs would have significant impact on reionization community!
GRBs as the standard candle

- correlation between isotropic energy $E_{\text{iso}}$ or luminosity $L_{\text{iso}}$ and spectral peak energy $E_{\text{peak}}$ has been known
  - Amati+’02; Yonetoku+’04

- This can be used as a standard candle, to make the Hubble diagram (distant vs. redshift), and then constrain cosmological parameters
  - constraint on cosmic expansion history, like SN Ia
  - many papers already appeared to give such constraints

- However, GRB results have not yet had a strong impact on the general cosmology community
  - why?
  - a critical view from a “cosmologist” point of view
Frontiers of Precision Cosmology

- $\Lambda$CDM universe already established

- next interest: the origin of the acceleration of cosmic expansion
  - dark energy (including the cosmological constant)?
  - modification of gravity theory on cosmological scale?

- Observational approach:
  - precise geometrical test to constrain the equation-of-state of dark energy (SN Ia, baryon acoustic oscillation, ...)
  - measurement of structure growth rate to test gravity theory
Geometrical Tests

- supernova Ia (standard candle)
  - now sufficient statistics
  - systematics limited!
  - a lot of effort for “standardization” for the next-generation cosmology

- baryon acoustic oscillation (standard ruler)
  - perhaps the “cleanest” geometrical test
  - expensive, requires > 100k galaxy redshifts in wide area
Measuring Structure Growth Rate: A Test of Gravity

- redshift space distortion (RSD) in galaxy redshift surveys
  - distortion by peculiar velocities
  - RSD gives a measure of structure growth rate \( f \)
    \[ = \frac{d(\ln \delta)}{d(\ln a)} \]
  - several measurements at \( z < 1 \)
  - will soon extend to \( z > 1 \)

- weak lensing experiments will also deliver growth rate measurements by wide field imaging surveys

2D correlation function in redshift space (Guzzo+’08)
Systematics of GRB standard candle

- The correlation (larger $E_{\text{iso}}$ or $L_{\text{iso}}$ for large $E_{\text{peak}}$) is in line with the selection effect about detector energy band

- It may not explain all the observed correlation, but should certainly affect the precise cosmological analysis!
SN Ia vs. GRB as standard candles

- GRBs are fundamentally stochastic events!
remarks on GRBs as a standard candle

- The physical origin of the spectrum-energy (luminosity) correlation is a very interesting issue.

- However, there are still many steps for GRBs as a standard candle to provide a result having a significant impact to the general cosmology community.

- Strength of GRB against SN Ia is reach to high-z
  - but, note that the standard dark energy appears at $z \lesssim 1$
GRBs as a Probe of Cosmic Opt./IR Background

- intergalactic absorption of high-energy gamma-rays gives an important measure of opt/NIR background, i.e., history of galaxy formation

- current limits come from blazars (z < 1)

- GRBs provide alternative background source, which would extend even higher-z
  - may probe star formation activity in reionization era (S. Inoue+’10)
  - highest-z blazars are at z~2, even by the Cerenkov Telescope Array (Y. Inoue +’10)
  - event rate may not be so large (~0.1-1 event/yr, Kakuwa+’11)
  - but may extend to z~4

Cerenkov Telescope Array