Probing the High Redshift Universe with GRBs

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Overview

- Background
- Detecting GRBs at VHR
- Probing SF with GRB afterglow
- Finding SN at VHR
- Measuring the redshifts of VHR GRBs
- Tracing Metallicity
- Probing Large-Scale Structure
- Determining Epoch of Reionization
- Conclusion
Constants

- Constants used are from WMAP1 results:
  - Total matter density $\Omega_M = 0.3$
  - Dark energy density $\Omega_\Lambda = 0.7$
  - Hubble constant $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$
Useful Acronyms

- GRB: Gamma-ray burst
- VHR: Very high redshift
- SFR: Star formation rate
- SNe: Supernova explosion
- BATSE: Burst and Transient Source Experiment on Compton Gamma Ray Observatory
- HETE - 2: High Energy Transient Explorer
- BeppoSAX: Italian-Dutch X-ray satellite
• Gamma-ray bursts (GRBs) are the most luminous events seen in the Universe
  – Bursts last from milliseconds to minutes
  – Followed by an afterglow at longer wavelengths
• Likely caused by shocked gas encountering magnetic fields and give off synchrotron radiation
Background

• GRB found with BeppoSAX (1997)
  – Afterglow contains X-ray, Optical, Radio components

• Light of GRB host galaxy is detected and is very blue (1998)
  – Implies GRBs may be associated with SF Galaxies

• GRB might contain an SN component (1999)
  – GRBs associated with core-collapse SN
Detecting GRBs at VHRs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Redshift</th>
<th>$P$ (photons cm$^{-2}$ s$^{-1}$)$^a$</th>
<th>$L_P$ (photons s$^{-1}$)$^b$</th>
<th>Redshift Reference</th>
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<td>2.3</td>
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<tr>
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<td>990712$^e$</td>
<td>0.430</td>
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<td>...</td>
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</table>

**TABLE 1**

**Peak Photon Fluxes and Isotropic Luminosities for GRBs with Secure Redshifts**
Detecting GRBs at VHRs

(1) \[ L_P = \int_{v_l}^{v_u} \frac{dL_P}{dv} \, dv \]

Peak photon number luminosity

(2) \[ P = \int_{v_l}^{v_u} \frac{dP}{dv} \, dv \]

Peak photon number flux

(3) \[ P = \frac{L_P}{4\pi D^2(z)(1 + z)^{\alpha}} \]

(4) \[ D(z) = c \int_0^z (1 + z') \left| \frac{dt(z')}{dz'} \right| \, dz' \]

Comoving distance to the GRB
Detecting GRBs at VHRs

\[
(5) \quad \frac{dt(z)}{dz} = -\left(\frac{c}{H_0}\right)\left\{\frac{1}{(1 + z)[\Omega_m(1 + z)^3 + \Omega_\Lambda + (1 - \Omega_m - \Omega_\Lambda)(1 + z)^2]^{1/2}}\right\}^{-1}
\]

\[
(6) \quad D(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1 + z')^3 + \Omega_\Lambda}}
\]

Taking \( \alpha = 1 \)

\[
P = \frac{L_P}{4\pi D^2(z)(1 + z)}
\]
Detecting GRBs at VHRs

![Graph showing detection rates for GRBs at various redshifts (log(1+z)) for different instruments: SWIFT, BATSE, and HETE-2. The graph displays the number of GRBs detected as a function of redshift.]
Detecting GRBs at VHRs

- Factors decreasing spectral energy flux:
  1. Distance away
  2. Redshift

- Factor increasing spectral energy flux:
  1. Time dilation
    - Space between GRB and observer decreases and amount of energy released over an hour is received in less time

- Effects cancel $\rightarrow$ little or no decrease in flux
Detecting GRBs at VHRs
Detecting GRBs at VHRs

GRB 970228 Early Afterglow at:
- $z = 1$
- $z = 3$
- $z = 5$
- $z = 10$
Detecting GRBs at VHRs

• Implications of light curve:
  – Detecting VHR GRBs require deep near-infrared observations
    • HETE-2 and Swift can do this
  – Deep optical observations needed to constrain the redshift
    • Looking for optical dropout
Probing Star Formation

• Collapsar model predicted GRBs caused by core-collapse SN
  – $\geq 40\ M_\text{solar}$ as a main sequence star
  – Must be rapidly rotating to develop jets
  – Low Z so that jets can strip off H-envelope and reach surface
Probing Star Formation

• Recall that in 1999, a SN component was detected in GRB afterglow
  – Suggests that GRBs are related to the deaths of massive stars
  – If GRBs related to collapse of massive stars then GRB rate proportional to SFR
  – Should occur out to $z \sim 10-20 \rightarrow$ Probe VHR star formation
Probing Star Formation
Probing Star Formation
Finding SN at VHR

- GRBs are likely caused by core-collapse SN
  - Therefore we should be able detect SN component if we know what to look for and when to look for it
Finding SN at VHR

![Graphs showing light curves for GRB 970228 Early Afterglow at different redshifts.](image1)

![Graphs showing apparent magnitudes at different redshifts.](image2)

**TABLE 2**

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Band</th>
<th>Time (days)</th>
<th>Magnitude</th>
<th>Flux Density (μJy)</th>
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<td>17</td>
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<td>...</td>
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<td>7.7</td>
<td>M</td>
<td>151</td>
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<td>0.026</td>
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Finding SN at VHR

![Graph showing apparent magnitude vs. log ν (Hz) with data points for different dates: 1999 Jun 29, 1999 Aug 19, 1999 Oct 2.]

The graph depicts the apparent magnitude plotted against logarithm of frequency (ν) in Hz. The data points indicate measurements taken on different dates, showing a trend over time.
Measuring GRB Redshifts

- There are 2 ways to measure the GRB redshift
  1. Taking spectrum of afterglow at early times
     - Lower-limit for measured redshift
  2. Taking spectrum of host galaxy
     - Not always easy to match host galaxy with GRB

- Both get harder to do at larger redshifts
Measuring GRB Redshifts
Measuring GRB Redshifts

• A possible third method:
  – Imagine a GRB at $z = 10$
    • Because of high redshift, the afterglow spectrum will be detectable in K-band
    • We will not detect signature in J-band due to drop-out from Ly$\alpha$ forest absorption

  – Therefore a ‘dark’ J-band switching on to ‘bright’ K-band is a signature of the GRB and can provide a good measure of the redshift
Tracing Metallicity

- Comparing GRBs to Quasi-stellar objects:
  - QSOs probe low Z of Halos and IGM
  - GRBs probe higher Z of disks and SF regions
Tracing Metallicity

• Two other metallicity studies:
  – Determine contribution from different SNe by looking at relative abundances of metals
  – Determine whether \([\text{Fe/H}]\) is a good chronometer at high redshift

• Probing metallicity at high redshifts requires extreme instrument sensitivity which is not doable any time soon
Probing Large-Scale Structure

• GRBs are useful because they are detectable at VHRs
  – But we would need a lot of recorded burst locations

• At such high redshifts there is not much large scale structuring yet (over-under densities much more modest at high $z$)
Probing Reionization

• Looking for signs of Gunn-Peterson Trough (GPT) in GRB spectra
  – GPT is the transition zone between where neutral H absorbs high flux of radiation and becomes ionized H
  – Location in redshift may point to mechanism of reionization
• Totani et al. paper put limit on reionization at $z > 6$ with GRB 05094 (2006)
Conclusion

• Background Findings:
  – GRB afterglow can be seen in x-ray, optical and radio
  – GRBs associated with SF
  – GRBs associated with core-collapse SNe
Conclusion

1. Detectability at VHR → have been detected out to $z \sim 6.4$ with Swift

3. Probing SF at VHR → can tell us where star forming regions are located and how active

5. Finding SN at VHR → has been confirmed at lower redshift and should work for high redshift
Conclusion

4. Measuring redshifts of GRB → looking for cut-off frequency method used to determine redshift of most distant GRB ever identified

5. Tracing metallicity → likely would take highly sensitive equipment and therefore not feasible

6. Tracing large-scale structure → need lots of recorded GRBs and not much out there to probe at high redshifts
Conclusion

7. Probing Reionization → seems to be a great method; have already changed constraints on reionization to $z>6$
Questions