Observations of Cosmic Dust Evolution Using GRB Afterglows:
The 2175 Å Carrier at z~3 and Supernova Dust at z~5

Daniel Perley (UC Berkeley)

Deciphering the Ancient Universe with Gamma-Ray Bursts

京都，日本
Introduction

- How does high-z dust differ from local dust?
  - How much dust at $z>3,4,5$? (When did most of it form?)
  - Does it have the same composition, size distribution, and observational signatures as dust today?
  - What can it tell us about conditions in early galaxies?

- **GRBs**: excellent tools for probing high-z dust
  - Extremely luminous: visible to extreme redshifts
  - Occur in “typical” star-forming galaxies
  - Intrinsically simple spectrum ($F = \lambda^\beta$)
\[ A_\lambda = 1.09 \, \tau(\lambda) \]

- Normalized to 5500Å (\( A_V \))
- Considerable local variation, esp. in UV

"2175 Å bump": can be dominant or totally absent

Varying slopes (reddening per dimming)
GRB 080607

An Ultra-Energetic Burst Piercing a Milky Way-like Molecular Cloud 2 Billion Years after the Big Bang

• ApJL 691:27 (arXiv/0901.0556)
• Add'l work in prep.

contributions from:
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Adam Miller
Adam Morgan
Mo Ganeshalingam
Weidong Li
Adria Updike
(+ others)
A Phenomenal Burst

- 15-150 keV fluence: $S = 2.32 \times 10^{-5}$ erg/cm$^2$ (7th highest of Swift mission)
- $z = 3.038$
- $E_{iso} = 1.87 \times 10^{54}$ erg (highest of Swift mission?)

BAT light curve (from Swift burst analyzer)
Afterglow

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Afterglow GRB 080607

Peak observed magnitude:

R~16, K~11.5

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Occurred during our Keck/LRIS night (classical, GRB host galaxies)

$t = 20$-$120$ min

low resolution, 3800-9200 Å

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Ionic Lines

z = 3.036

- Carbon
- Chlorine
- Copper
- Nickel
- Potassium
- Silicon
- Sulfur
- Hydrogen (Ly α)
- Magnesium
- Aluminum
- Gallium
- Lead
- Iron
- Germanium
- Phosphorous
- Chromium
- Nickel
- Zinc
- Titanium
- Manganese
- Cobalt
- ???
Ionic Lines

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$z = 3.036$

$Z >$ solar

Hydrogen (Ly $\alpha$)

Sulfur

Silicon

Potassium

Nickel

Copper

Chlorine

Carbon

Manganese

Titanium

Zinc

Nickel

Silicon

Hydrogen

Gallium

Lead

Iron

Germanium

Aluminum

Magnesium

Phosphorous

Chromium

Cobalt

$Z \geq$ solar

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Molecular Lines

z = 3.036

Molecular hydrogen (H₂)

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Vibrationally Excited $H_2$

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$d = 230–940$ pc
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**Curvature**

- **z = 3.036**
- **Molecular hydrogen (H₂)**
- **Hydrogen (Ly α)**
- **Silicon**
- **Sulfur**
- **Carbon**
- **Potassium**
- **Nickel**
- **Chlorine**
- **Copper**
- **Gallium**
- **Lead**
- **Iron**
- **Germanium**
- **Aluminum**
- **Titanium**
- **Zinc**
- **Nickel**
- **Monoxide**
- **Phosphorous**
- **Manganese**
- **Cobalt**
- **Magnesium**
- **Carbon Monoxide**
- **Molecular hydrogen (H₂)**
- **Potassium**
- **Nickel**
- **Copper**
- **Gallium**
- **Lead**
- **Iron**
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Spectral Energy Distribution

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Extinction Modeling

SMC

Calzetti (starburst)

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Extinction Modeling

- SMC
- Calzetti
- Milky Way
- LMC

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Extinction Modeling

Solve for extinction law using general Fitzpatrick parameters:

- $A_v = 3.2 \pm 0.5$
- $R_v = 4.0 \pm 0.2$
- $c_3 = 1.3 \pm 0.3$
- $c_4 = 0.3 \pm 0.1$
Extinction Law

- GRB 080607
- Av = 3.2 ± 0.5
- $R_V = 4.0 ± 0.2$
- $c_3 = 1.3 ± 0.3$
- $c_4 = 0.3 ± 0.1$

Starburst galaxies

- SMC
- LMC
- MW (diffuse ISM)
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Av = 3.2 ± 0.5
Rv = 4.0 ± 0.2
\[ c3 = 1.3 ± 0.3 \]
\[ c4 = 0.3 ± 0.1 \]

- Very large extinction column
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2009

Extinction Law

Av = 3.2 ± 0.5
Rv = 4.0 ± 0.2
c3 = 1.3 ± 0.3
c4 = 0.3 ± 0.1

- Very large extinction column
- Relatively UV-grey (many large particles)
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Extinction Law

**Av** = 3.2 ± 0.5

**Rv** = 4.0 ± 0.2

**c3** = 1.3 ± 0.3

**c4** = 0.3 ± 0.1

- Very large extinction column
- Relatively UV-grey (many large particles)
- 2175 Å bump weak but present

Observations of Cosmic Dust Evolution using GRBs
Extinction Law

- **Av** = 3.2 ± 0.5
- **Rv** = 4.0 ± 0.2
- **c3** = 1.3 ± 0.3
- **c4** = 0.3 ± 0.1

**Similar to Galactic molecular cloud sightlines.**

- 2175 Å bump weak but present
GRB 080607:

- Large dust column in star-forming galaxy at $z>3$
- Probing sightline through molecular cloud
- Solar metallicity, dust resembles MW, LMC but not SMC, suggesting similar conditions to now: mature, dusty star-forming galaxy?
- Highest-redshift detection of $2175\,\text{Å}$ feature: carrier was formed (in part) by $t = 2\,\text{Gyr.}$
GRB 071025

Supporting Evidence for a Transition in Dust Properties in the first \(~1\) Gyr

MNRAS in press (arXiv/0912.2999)

contributions from:

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P. Wozniak
Thomas Vestrand
Grant Williams
Thomas Kruhler
Adria Updike
(+ others)

PAIRITEL
REM
MAGNUM
RAPTOR
Kuiper
GROND

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Light Curve

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XRT

K, H, J, I clear, Y, R

AB magnitude vs. time (t) in seconds (s)

$10^2$ $10^3$ $10^4$ $10^5$

$10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$F_v$ (Jy, J)

Light Curve
R-band faintness cannot be reproduced by any dust model:
photometric redshift $z = 4.8 \pm 0.4$
GRB 071025

Spectral Energy Distribution

R-band faintness cannot be reproduced by any dust model:

photometric redshift

$z = 4.8 \pm 0.4$
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Spectral Energy Distribution

$\lambda_{\text{eff, rest}}$ (Å)

magnitude (AB)

$F_V$ ($\mu$Jy)

$\lambda_{\text{eff}}$ (Å)

20000

10000

200

100

50

4000

18.0

18.5

19.0

19.5

20.0

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SED is inflected: flattens around $\lambda_{\text{rest}} \sim 2000$ Å

I-band faintness is not due to DLA (HIRES spectrum)
Extinction Modeling

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Milky Way

LMC

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Extinction Modeling

Maiolino

Empirical law from a SDSS z=6.2 quasar: well fit by models of dust from Type II SNe

Av = 0.55 ± 0.1
Extinction law

- SMC
- LMC
- MW (diffuse ISM)
- Starburst galaxies
- Maiolino
The significance of this critically depends on accurate calibration and understanding of systematic uncertainties!

e.g., GRB 050904:
- Stratta et al.: Maiolino dust
- Kann et al.: no dust
- Gou et al.: no dust
- Liang and Li: 2175 Å bump?
- Zafar: no dust
The significance of this critically depends on accurate calibration and understanding of systematic uncertainties!

SED features do not change with time and are seen with multiple instruments in geographically different locations.

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- SED features do not change with time and are seen with multiple instruments in geographically different locations.

**Is it real?**

- **GRB 050904**: Stratta et al.: Maiolino dust
  - Kann et al.: no dust
  - Gou et al.: no dust
  - Liang and Li: 2175 A bump?
Is it real?

The significance of this critically depends on accurate calibration and understanding of systematic uncertainties!

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- Zafar: no dust

Examined:
- zeropoint uncertainty
- 2MASS survey systematic uncertainty
- instrumental color terms
- variable atmospheric absorption
- non-power law intrinsic spectrum
- strong DLA at z=5.2

none of these are significant enough to generate the observed effect.
Dust Transition at High $z$?

**Conclusions**

**Extinction Law Class**
- Maiolino plateau
- Featureless, steep
- Featureless, shallow
- Gray
- Shallow w/ 2175
- Steep w/ 2175

**Redshift**
- $z = 0$
- $z = 2$
- $z = 4$
- $z = 6$

**Dust Observations**
- GRB 051111
  - Butler et al. 2007
- SDSS quasars
  - Hopkins et al. 2004
- AGN?
  - Schady et al. 2010, Kann et al. 2007
- Nearby starbursts
  - Calzetti et al. 1994
- Nearby spirals
  - Keel & White 2001, Bianchi et al. 1996
- Milky Way (mean)
  - LMC
- Milky Way (clouds)
  - SMC
- GRB 061126
  - Perley et al. 2008
- GRB 070802
  - Eliasdottir et al. 2009
- GRB 071025
  - Perley et al. 2010
- GRB 080607
  - Prochaska et al. 2009
- SN hosts
  - Poznanski et al. 2009, Elias-Rosa et al. 2006
- Lensing galaxies
  - Falco et al. 2009

**References**
- Butler et al. 2007
- Calzetti et al. 1994
- Poznanski et al. 2009
- Elias-Rosa et al. 2006
- Prochaska et al. 2009

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Dust Transition at High z?

Conclusions

Extinction Law Class

- Maiolino plateau
- Featureless, steep
- Featureless, shallow
- Gray
- Shallow w/ 2175
- Steep w/ 2175

Redshift

- t > 1 Gyr: z < 5
- Dust forms in AGB stars
- z = 0
- z = 2
- z = 4
- z = 6
- Dust forms in SNe?
- GRB 051111
- GRB 071025
- GRB 080607
- GRB 070802

Other References:
- Poznanski et al. 2009,
- Elias-Rosa et al. 2006
- Calzetti et al. 1994
- Butler et al. 2007
- Perley et al. 2010
- Maiolino et al. 2004
- Perley et al. 2008
- Hopkins et al. 2004
- Gaskell et al. 2007
- Prochaska et al. 2009
- Eliasdottir et al. 2009
- Falco et al. 2009
- Keel & White 2001,
- Bianchi et al. 1996

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Conclusions

Dust Transition at High z?

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<th>Redshift</th>
<th>Extinction Law Class</th>
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<td>$z &lt; 5$</td>
<td>Dust forms in AGB stars</td>
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<tr>
<td>$z &gt; 5$</td>
<td>Dust forms in SNe?</td>
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$t > 1$ Gyr: Dust forms in AGB stars
$t < 1$ Gyr: Too early to be sure, but trend is intriguing!
Conclusions

- Diffuse MW / LMC / SMC is not the whole story
- 080607: Galactic-like molecular cloud at z=3 with weaker 2175 Å carrier
- 071025: Plenty of dust at z=5, extinction law resembles z>5 quasars and modeled dust from Type II Sne
- SN → AGB production transition at z~5?
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Extinction Law

Av = 3.2 ± 0.5
Rv = 4.0 ± 0.2
c3 = 1.3 ± 0.3
c4 = 0.3 ± 0.1

080607

ONC

LMC

SMC

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c2 (UV steepness)
c3 (2175 bump strength)

Inverse wavelength (1/μm)
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Extinction Law

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- Av = 3.2 ± 0.5
- Rv = 4.0 ± 0.2
- c3 = 1.3 ± 0.3
- c4 = 0.3 ± 0.1

Typical MW-like values, except:

- Large Rv: dense ISM (like a molecular cloud!)
- Low but nonzero c3: presence of 2175 Å carrier (graphite grains?)