Gamma-Ray Bursts as Cosmological Tools

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Outline

✓ A brief history of time & the Universe
✓ Introduction to Astrophysical notions & definitions
✓ Gamma-Ray Bursts (GRBs)
✓ Can GRBs serve as standard candles?

Example of human error:
The Same Color Illusion
Astronomy Picture of the Day
2007 July 17
Example of human error:
The Same Color Illusion
Astronomy Picture of the Day
2007 July 17
Example of Instrumental bias: 
**Malmquist Bias**
Big discovery!

Strong evolution of galaxy brightness with distance

Nature submitted!
Nature rejected!
Malmquist Bias

Detector Threshold

Intrinsic Brightness

Distance
Edwin Hubble, Astronomer, 1925

✓ The Universe is unimaginably huge

✓ The Universe is expanding

✓ It had a beginning 13.7 billion years ago

✓ The visible size of the universe:

$13.75 \pm 0.11$ billion light years

or

$1.3 \times 10^{26} m$
How did Hubble discover the expansion of the Universe?
Possible Models of the Expanding Universe

- Decelerating Universes
- Coasting Universe
- Accelerating Universe
How to find the correct cosmological model?

- **Cosmological Standard Candle**
  - Constant Luminosity known
  - Spectroscopic Redshift known

Different cosmological models lead to different definitions of distance,

\[ D_L = \sqrt{\frac{1}{4\pi}} \frac{\text{Intrinsic Luminosity}}{\text{observed brightness}} \]

\[ D_L = \frac{C}{H_0} (1 + z) \int_0^z dz' \left[ (1 + z')^3 \Omega_M + \Omega_\Lambda \right]^{-\frac{1}{2}} \]
Type-Ia Supernovae as Cosmological Standard Candles

SN 2006X, before and after the Type Ia Supernova Explosion (Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)

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Supernovae
Hubble diagram,
Kirshner 1999, PNAS, 96, 4224

Dark Matter
73%
Dark Energy
23%
Stars, human, cat, ...
0.4%
Intergalactic Gas
3.6%

SNe Ia
High-z SN Search
Possible Models of the Expanding Universe

- Decelerating Universes
- Coasting Universe
- Accelerating Universe

Expansion Rate $> 0$
How to constrain the expansion rate of the universe in the distant universe?

Candidate Standard Candle: 
Gamma-Ray Bursts (GRBs)  
Supernovae projects: $Z < 1.7$
Gamma-Ray Bursts (GRBs)

- Discovered by Vela nuclear test detection satellite (1960s), Top-Secret project before the collapse of USSR

- The most powerful explosions in the Universe

\[ 10^{47} \text{ergs} < E_{\text{iso}} < 10^{55} \text{ergs} \]
Total energy release of the Sun during 10 billion years: $10^{51}$ ergs
**GRB types**

- **Short-duration GRBs (SGRBs):** possibly the merger of binary neutron stars
- **Long-duration GRBs (LGRBs):** possibly related to the death of supermassive stars
Long-duration GRB (LGRB)
Short-duration GRB (SGRB)
Duration distribution of 1900 BATSE GRBs

$T_{90}$ [sec]

Number

SGRB  LGRB
Credit: Edo Berger, Harvard CfA
GRB light-curve diversity
Example of GRB Spectrum

Kaneko et al. (2006)
Example of GRB Power Spectrum

Kaneko et al. (2006)

$E^2 \times \text{Flux vs. } E$

GRB spectral peak energy $E_{P,\text{obs}}$
Shahmoradi & Nemiroff (2010)

Lower $E_{p,\text{obs}}$ ≡ softer

Higher $E_{p,\text{obs}}$ ≡ harder
Amati (2002)

The Amati Relation

### Graph

- **Vertical Axis:** $E_p$ (keV)
- **Horizontal Axis:** $E_{\text{rad}}$ (erg)

The graph shows a linear relationship between $E_p$ and $E_{\text{rad}}$. Data points and error bars are plotted on the graph.
The Amati Relation

GRBs as cosmological tools?!

✓ Cosmological Standard Candle
✓ Constant Luminosity known
✓ Spectroscopic Redshift known
Standard Candle Observer

$$D_{L,\text{obs}} = \sqrt{\frac{1}{4\pi} \frac{E_{\text{iso}}(E_{p,\text{int}})}{S_{\text{bol}}}}$$

The GRB Hubble Diagram
Liang, et al. (2008)
Problems with GRB relations

- No physical basis for GRB relations to date
- Frequent number of outliers to these relations
  - All authors have overlooked outliers to these relations in their GRB Hubble diagrams.
The Amati Relation

Short-duration GRBs (SGRBs)

Long-duration GRBs (LGRBs)
The Amati Relation

$E_{p,\text{int}}$ [KeV] vs $E_{\text{iso}}$ [erg]

- Spectrally analyzed
- Not analyzed

2704 BATSE GRBs

$10^4$ $10^5$ $10^6$

$10^46$ $10^48$ $10^50$ $10^52$ $10^54$ $10^56$
Selection effects?
Red: 25 - 50 keV
Yellow: 50 - 100 keV
Green: 100 - 300 keV
Blue: > 300 keV

Brightness ($S$)

$$HR_H = \frac{S_{Blue} + S_{Green}}{S_{Yellow} + S_{Red}}$$
Shahmoradi & Nemiroff (2010) GRB brightness

SGRBs dimmer & harder

LGRBs brighter & softer

2130 BATSE GRBs

$HR_H$

$S_{bol}$ [erg]
Parameter estimation based on Bayes Theorem and Markov Chain Monte Carlo techniques.

Posteriors distributions of the parameters of the truncated multivariate normal distributions considered for the spectral parameters of the 3 GRB models: Band, COMP(CPL) & SBPL.
Parameter estimation based on Minimum $\chi^2$ & Minimum Kolmogorov-Smirnov distance techniques.

Marginalized likelihood contour plots of the observed data given different parameter values of the truncated multivariate normal distribution assumed for the spectral parameters of the three GRB models.
Shahmoradi & Nemiroff (2009)

2130 BATSE GRBs
2130 BATSE GRBs
Fuzzy Cluster Analysis
Sum of All Normalized Determinants (SAND), Rousseeuw et al. (1996)
Selection effects due to impossibility of spectral analysis.
Selection Effects due to GRB Detectors?

✓ BATSE (1990-2000)
The Amati Relation

Selection effects due to detector thresholds, impossibility of spectral analysis, and redshift measurement


Physical origin

Summary & Conclusions

✓ Gamma-Ray Bursts are the most powerful events of the Universe, possibly related to the death of super-massive stars.

✓ Several correlations among the spectral parameters of GRBs have been proposed, such as the Amati relation.

✓ Numerous attempts have been made by different authors to use these relations to construct the Hubble diagram.

✓ The result of our analyses, however, provide the first direct evidence that the Amati & Ghirlanda relations do not have physical origins and to our estimates, these relations hold as inequalities.

✓ Although the utility of the Amati relation in cosmology is questioned, GRBs -- expected to be detectable out to $z \sim 65$ -- might still hold the promise as the unique probes of the early universe. Further analysis coming up soon...
General Conclusions
(Applicable to any field of Science)

✓ **Outliers! Take them seriously in data analysis.**

✓ **Strong Correlation, No Outlier! Then why should there be such strong**

![Graph showing Instrumental effects or Physical origin?]
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References

@article{shahmoradi2015short,
    title={Short versus long gamma-ray bursts: a comprehensive study of energetics and prompt gamma-ray correlations},
    author={Shahmoradi, Amir and Nemiroff, Robert J},
    journal={Monthly Notices of the Royal Astronomical Society},
    volume={451},
    number={1},
    pages={126--143},
    year={2015},
    publisher={Oxford University Press}
}

@inproceedings{shahmoradi2014similarities,
    title={On the similarities of the prompt gamma-ray emissions in Short and Long Gamma-Ray Busts},
    author={Shahmoradi, Amir},
    booktitle={APS April Meeting Abstracts},
    year={2014}
}
@inproceedings{nemiroff2009causes,
title={What Causes GRB Time Dilation?},
author={Nemiroff, Robert and Shahmoradi, Amir},
booktitle={AIP Conference Proceedings},
volume={1133},
number={1},
pages={323--327},
year={2009},
organization={AIP}
}

@inproceedings{shahmoradi2009real,
title={How Real detector thresholds create false standard candles},
author={Shahmoradi, Amir and Nemiroff, Robert},
booktitle={AIP Conference Proceedings},
volume={1133},
number={1},
pages={425--427},
year={2009},
organization={AIP}
}
References

@inproceedings{nemiroff2010detection,
  title={Detection Threshold Effects on GRBs as a Cosmological Standard Candle},
  author={Nemiroff, Robert J and Shahmoradi, A},
  booktitle={Bulletin of the American Astronomical Society},
  volume={42},
  pages={228},
  year={2010}
}

@article{shahmoradi2010hardness,
  title={Hardness as a spectral peak estimator for gamma-ray bursts},
  author={Shahmoradi, Amir and Nemiroff, Robert J},
  journal={Monthly Notices of the Royal Astronomical Society},
  volume={407},
  number={4},
  pages={2075--2090},
  year={2010},
  publisher={Blackwell Publishing Ltd Oxford, UK}
}
@inproceedings{miller2011quantifying,
title={Quantifying GRB Pulse Shape Evolution to Study the Pulse Scale Conjecture},
author={Miller, Daniel and Nemiroff, RJ and Holmes, J and Shahmoradi, A},
booktitle={Bulletin of the American Astronomical Society},
volume={43},
year={2011}
}

@inproceedings{shahmoradi2011cosmological,
title={A Cosmological Discriminator Designed to Avoid Selection Bias},
author={Shahmoradi, Amir and Nemiroff, RJ},
booktitle={Bulletin of the American Astronomical Society},
volume={43},
year={2011}
}
@article{shahmoradi2011vizier,
title={VizieR Online Data Catalog: Gamma-ray bursts spectral peak estimator (Shahmoradi+, 2010)},
author={Shahmoradi, A and Nemiroff, RJ},
journal={VizieR Online Data Catalog},
volume={740},
year={2011}
}

@article{shahmoradi2011possible,
title={The possible impact of gamma-ray burst detector thresholds on cosmological standard candles},
author={Shahmoradi, A and Nemiroff, RJ},
journal={Monthly Notices of the Royal Astronomical Society},
volume={411},
number={3},
pages={1843--1856},
year={2011},
publisher={Blackwell Publishing Ltd}
References

@article{shahmoradi2013multivariate,
  title={A Multivariate Fit Luminosity Function and World Model for Long Gamma-Ray Bursts},
  author={Shahmoradi, Amir},
  journal={The Astrophysical Journal},
  volume={766},
  number={2},
  pages={111},
  year={2013},
  publisher={IOP Publishing}
}

@article{shahmoradi2013gamma,
  title={Gamma-Ray bursts: Energetics and Prompt Correlations},
  author={Shahmoradi, Amir},
  year={2013}
}

@inproceedings{shahmoradi2014classification,
  title={Classification and Energetics of Cosmological Gamma-Ray Bursts},
  author={Shahmoradi, Amir and Nemiroff, RJ},
  booktitle={American Astronomical Society Meeting Abstracts\# 223},
  volume={223},
  year={2014}
}
Thank you!

Questions?

Photo: Alborz Mountain, Northern Persia