The Impact of Positional Uncertainty on Gamma-Ray Burst Environment Studies

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Topics in AstroStatistics
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Image credit: Gemini Observatory/AURA/Lynette Cook
Outline

● Background
  – What are GRBs?
  – Host Galaxy Environment Studies

● Impact of Positional Uncertainty on:
  – Host Galaxy Identification
  – Location Measurements

● Results
  – Progenitor Implications

● Conclusions
What are Gamma-Ray Bursts?

- The Universe's most energetic explosions
- Prompt emission $\rightarrow$ long vs. short duration GRBs
- Afterglow emission $\rightarrow$ spans X-ray to visible to radio wavelengths

Progenitor models
- Collapsar model (Woosley et al. 1993) $\rightarrow$ long GRBs
- Merging NS-NS binaries (Eichler et al. 1989) $\rightarrow$ short GRBs
Studying the Locations of Transients

- A complementary approach to studying the events themselves
  - Pre-explosion imaging to study progenitor star
  - Infer progenitor properties by studying host environments

Kelly et al. 2008
Long GRB Host Galaxy Studies

- Global Host Properties
  - Irregular, faint, blue star-forming galaxies
- Sub-Galactic Environment Studies
  - Population studies
    - Offset from center of host galaxy
    - Fractional Flux
      - Statistic measuring the brightness of the burst location relative to the host light distribution
  - Comparisons to Supernovae

This project → analyzed the last 10 years of HST observations of ~100 long GRBs to investigate their preferred locations within their host galaxies
Relative Astrometry

- Positional uncertainty comes from astrometric match uncertainty and uncertainty on the GRB position

Late-time Hubble image of host galaxy

Early-time ground-based afterglow detection
Relative Astrometry

- Positional uncertainty comes from astrometric match uncertainty and uncertainty on the GRB position
Host Galaxy Assignment

- Probability of chance coincidence (PCC)
  - Based on observed number density of field galaxies
  - PCC depends on galaxy brightness, offset, and positional uncertainty

\[ P_{cc} = 1 - e^{-\pi R_e^2 \sigma(\leq m)} \]

- Luminosity argument based on \textit{a priori} host information
- Is the host candidate's luminosity consistent with the distribution observed for bursts with secure host associations?
Offset Measurements

- Measure afterglow and host galaxy centroids
- Calculate the offset ($R$) of the afterglow from the host center

$$\sigma_R = \sqrt{\sigma_{\text{tie}}^2 + \sigma_{\text{OT}}^2 + \sigma_{\text{host}}^2}$$

- Individual offsets described by Rice Distribution

$$p(x|R, \sigma_R) = \frac{x}{\sigma_R^2} \exp \left[ -\frac{(x^2 + R^2)}{2\sigma_R^2} \right] I_0 \left( \frac{xR}{\sigma_R^2} \right)$$

- To assess the impact of the uncertainties on the offset distribution I use a Monte Carlo simulation

$R = 0.54$
$\sigma_R = 0.80$
Distribution of Offsets

Left:
- Normalized Offset
- $p(x|R, \sigma_R)$

Right:
- Normalized Offset
- Summed Distribution
- Exp. Disk PDF
Offset Measurements

- True offset and offset uncertainty should be unrelated
- Bias to large offsets when offset uncertainty is large
Cumulative Offset Distribution

- Comparison with exp. disk profile and various types of supernovae explosions

- LGRBs prefer the bright central regions of their hosts
- 50% of LGRBs occur within a region of their hosts containing 33% of the light

SNe data from Kelly and Kirshner 2012, SLSNe data from Lunnan et al. 2015
Fractional Flux Measurements

- Technique to assess spatial coincidence with bright or faint regions
- Fractional Flux = Flux from pixels fainter than burst site / Total galaxy flux
- Extract galaxy pixels and measure burst site flux
Effect of Positional Uncertainty on Fractional Flux

- Can you still constrain the FF value as your knowledge of the burst location decreases?

- Bayesian approach
  - Likelihood = 2D-Gaussian positional uncertainty distribution
    - Each pixel has an associated probability that the burst occurred there
  - Prior = Unif[0,1]
  - Posterior = probability distribution of FF values
Case Studies: GRBs 050820 and 060912A

- Vary size of error circle
- Distribution changes significantly
Effect on Full Sample

- Bias to low FF values when the error circle area > 10% galaxy area
Fractional Flux Distribution

- Comparison with various types of supernova explosions

- Median = 0.75
- Agreement with Type Ic SNe
- Possible connection to SLSNe?

LGRBs – F06, CCSNe, SLSNe, and II/Ic SNe data from Fruchter et al. 2006, Svensson et al. 2010, Lunnan et al. 2015, and Kelly et al. 2008
Fractional Flux – Offset Relationship

- **FF-Offset correlation** indicates high fractional flux preference is entirely due to bursts at small offsets
  - Bursts at large offset show no preference for unusually bright regions

Ic SNe and CCSNe data from Kelly et al. 2008 and Svensson et al. 2010, respectively

**Graphical Description**

- The graph shows a scatter plot of fractional flux against host-normalized offset ($R_{\text{norm}}$).
- Cumulative distribution plots for different categories of SNe (Ic SNe with $R_{\text{norm}} > 0.5$, $R_{\text{norm}} \leq 0.5$, and CCSNe).

**Key Points**

- FF-Offset correlation suggests high fractional flux preference is due to bursts at small offsets.
- Bursts at large offsets show no preference for unusually bright regions.

**Legend**

- **Red circles** represent data from this work.
- **Blue triangles** represent Type Ic SNe.
- **Red line** with markers represents $R_{\text{norm}} > 0.5$.
- **Red dashed line** represents $R_{\text{norm}} \leq 0.5$.
- **Light blue line** represents Ic SNe with $R_{\text{norm}} > 0.5$.
- **Dashed blue line** represents Ic SNe with $R_{\text{norm}} \leq 0.5$.
- **Blue solid line** represents CCSNe.
Summary and Conclusions

- Analyzing the locations of GRBs within their host galaxies requires a careful consideration of positional uncertainty
  - Large uncertainties lead to:
    - the prevention of robust host associations
    - a bias to large offsets
    - a bias to low fractional flux
- Long GRBs are more centrally concentrated than the underlying light distributions of their host galaxies
  - Star formation near the central regions of their hosts is most favorable for long GRB production
- The preference for high fractional flux is due to long GRBs at small offsets
- An environmental factor such as an increased massive binary fraction may be at play in the central regions of long GRB hosts
Host Galaxy Assignment

- Luminosity argument based on *a priori* host information
- Is the host candidate's luminosity consistent with the distribution observed for bursts with secure host associations?