Optical observations of GRB afterglows

Shashi B. Pandey

IAA, Granada, Spain
Plan of the talk

- Introduction to afterglows of GRBs
- Observations of optical afterglows
- LCs and SEDs of afterglows
- Modeling of afterglows
- Results
Afterglows of GRBs

- Relativistic shells ejected from the central engine, form shocks, convert their kinetic energy into radiation.

- Shocks interact with ISM, emits non-thermal synchrotron radiation ranging from X-ray, optical to radio known as afterglows.
Importance of afterglow observations

- Long baseline in temporal and spectral domains
- Indirect probe to know about the progenitor
- Surroundings, distance and energetics
- Host galaxies
- Multi-band afterglow modeling \((\text{ISM Vs. WIND})\)
Basic GRB afterglow theory

The energy distribution of the injected electrons is a power-law:

\[ N(\gamma_e) \propto \gamma_e^{-p}, \quad \gamma_m < \gamma_e < \gamma_u \]

\[ p, \text{ the electron energy index} \]

Theoretical spectral energy distribution of GRB afterglows (Synchrotron radiation)
(Sari Piran & Narayan 1998)
Possible progenitors

Hyperaccreting Black Holes

- NS - NS merger
- BH - NS merger
- BH - WD merger
- NS/BH - He core merger after common envelope
- collapsar = rotating, collapsing "failed" supernova
Jet Signatures - I

Output γ-ray energy & No. of bursts

\[ E_\gamma = (1 - \cos \theta_j) \ E_{\text{iso,}\gamma} \]

Achromatic break in observed LCs

\[ f_\gamma(t) = 2^{1/s} f_0 / [(t/t_j)^{\alpha_1s} + (t/t_j)^{\alpha_2s}]^{1/s} + f_g \]

\[ \theta_j \]
Jet Signatures - II

Massive ($M > 25_{\text{sun}}$), Stellar Collapse simulations

Jet powered by newly formed central Black Hole emerging from the stellar envelope. The envelope is eventually expelled in a supernova (hypernova?)


Signatures of “Two-Jet model”
Jet structure, UJ & USJ Models

Universal Structured Jet

Uniform Jet
GRB Optical afterglow observations

Since Jan 99, we probed > 30 fields from IPN, BeppoSAX, HETE, INTEGRAL

Observed 13 afterglows, from Jan 1999 to May 2003, presented in the Thesis

Using CCD (1K*1K, 2K*2K & 2K*4K), in UBVRI filters

Photometry/ Spectroscopic data reductions using standard packages IRAF, MIDAS and DAOPHOT-II

Calibrations using our own secondary standards in most of the GRB fields

Calibrations and data are published in
(Sagar R. et al. 2001a,b, 2002 and Pandey S. B. et al. 2003a,b & 2004)
The Optical facilities used

1.04m, ST, Naini Tal  
f/13 Cassegrain

2.01m, HCT, IAO  
f/9 Cassegrain

2.34m, VBT, Kavalur  
f/13 Cassegrain
Importance of geographical location of India for GRB afterglow observations
# List of observed optical afterglows of GRBs

<table>
<thead>
<tr>
<th>(GRB Name)</th>
<th>(Filters Observed)</th>
<th>(Localizations by)</th>
</tr>
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<tr>
<td>GRB 990123</td>
<td>BVR</td>
<td>BeppoSAX/ WFC</td>
</tr>
<tr>
<td>GRB 991208</td>
<td>I</td>
<td>Uly/ Konus/ NEAR</td>
</tr>
<tr>
<td>GRB 991216</td>
<td>R</td>
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<td>VRI</td>
<td>ASM/ Uly</td>
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<td>GRB 000926</td>
<td>R</td>
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<td>GRB 010222</td>
<td>VRI</td>
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<tr>
<td>GRB 011211</td>
<td>R</td>
<td>BeppoSAX/ WFC</td>
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<tr>
<td>GRB 020405</td>
<td>I</td>
<td>Uly/ MO/ BeppoSAX</td>
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<tr>
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<td>BVRI</td>
<td>HETE-II</td>
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<tr>
<td>GRB 021211</td>
<td>BVRI</td>
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<td>GRB 030226</td>
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<td>GRB 030227</td>
<td>R</td>
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<td>GRB 030328</td>
<td>BVRI</td>
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</tr>
<tr>
<td>GRB 030329/ SN 2003dh</td>
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Observational facts from optical afterglows

**Afterglow Light-curves**

- Break in the afterglow light-curves
- Superimposed variability
- Late time flattening due to underlying host galaxy
- Late time SN-bumps

**Spectral energy distributions**

- Tells about the location of break frequencies $\nu_c$ and $\nu_m$
- Spectral slope $\beta$, in combination with temporal slopes $\alpha$
can tell about the electron energy index $p$
- Deviation from expected power law due to reddening in different regime tells about intrinsic host extinction
In the synchrotron afterglow model, temporal slope $\alpha$ & spectral slope $\beta$ are observed as a power-law decay

related as $F_{\nu}(t, \nu) \propto t^{-\alpha} \nu^{-\beta}$, with no spectral breaks.

$\alpha$ and $\beta$ are function of $p$, the power law exponent of the electron Lorentz factor.

### Models

- **Isotropic emission**  

- **Non-isotropic emission**  
Breaks in the afterglow LCs

Passage of break frequencies through observed frequency, chromatic

\[ \Delta \alpha = \frac{1}{4}, \text{passage of cooling break through observed frequency} \]

Jet break, achromatic

A. Beaming angle \( \frac{1}{\Gamma} \) exceeds collimation angle \( \theta \) (Geometric effect)

light curve steepening \( \Delta \alpha = \alpha_1 - \alpha_2 = (3 - s)/(4 - s) \)

( \( s = 0 \) for ISM & \( s = 2 \) for WIND) (Panaitescu Meszaros & Rees 1998)

B. Sideways expansion of the jet (Due to Dynamical evolution)

late time temporal slope \( \alpha_2 = p \) (Rhoads, 1999)
\( \alpha, \beta \) and \( p \) relations

1. Before jet break
   \( \text{if } v_m < v < v_c, \alpha_1 = \frac{3(p - 1)}{4}, \beta = \frac{p - 1}{2}, \alpha_1 = \frac{3\beta}{2} \)
   \( \text{if } v > v_c, \alpha_1 = \frac{3p - 2}{4}, \beta = \frac{p}{2}, \alpha_1 = \frac{3\beta}{2} - \frac{1}{2} \)

2. After jet break
   \( \text{if } v_m < v < v_c, \alpha_2 = p, \beta = \frac{p - 1}{2}, \alpha_2 = 2\beta + 1 \)
   \( \text{if } v > v_c, \alpha_2 = p, \beta = \frac{p}{2}, \alpha_2 = 2\beta \)

Sari Piran & Halpern (1999)
GRB 000301C, afterglow LCs

- Achromatic break is clear in all passbands
- Averaged temporal slopes $\alpha_1 = 1.2\pm0.1$, $\alpha_2 = 3.0\pm0.5$ and $t_j = 7.6\pm0.06$ day
- Explained in terms of ISM Jet model
  Predictions in combination with spectral index, except the overlapped variability

GRB 000301C, Sagar et al., (2000)
Spectral slope $\beta$ from optical data with other frequencies can be used to constrain the break frequencies $\nu_m$ and $\nu_c$ and electron energy index $p$.

In this case, at $\Delta t = 4.8$ day, $\beta = 0.73 \pm 0.06$ $E(B-V) = 0.05$ mag, Galactic extinction.

Cooling frequency $\nu_c$ is above optical at the epoch. It is clear from the single spectral slope from IR - optical bands.

Maximum synchrotron frequency $\nu_m$ seems to lie in millimeter region.
GRB 021004, afterglow LCs

Used $t > 2$ data only to determine parameters

$\alpha_1 = 0.99 \pm 0.05$, $\alpha_2 = 2.0 \pm 0.2$, $t_j = 6.5 \pm 0.2$ day

Early 3 data points in R band are explained
Due to reverse shock emission

Late time host galaxy contribution is clear

Pandey et al., 2003
GRB 021004, afterglow SED

SED at 1.37 day, Galactic E(B-V) = 0.02 mag

$\nu_c \sim 6.9 \times 10^{15} \text{ Hz}$, $p = 2.27$, $E(B-V) = 0.2 \text{ mag}$

This SED determines Host extinction in the burst direction and determined parameters are explained in terms of ISM Jet model (UJ)
GRB 030226, afterglow LCs

- $\alpha_1 = 0.67 \pm 0.02$, $\alpha_2 = 2.5 \pm 0.03$, $t_j = 0.86 \pm 0.03$ day

- Determined spectral index $\beta$ and so the electron energy index $p \sim \alpha_2$

- Explained in terms of sideways expansion of jet

- Our photometric calibrations don’t indicate for density-jump in the ambient medium. (Dia & Wu 2003)

GRB 030226, afterglow SED

Present case, around jet break, using BVRIK data, spectral slope $\beta = -0.82 \pm 0.0$, small Galactic $E(B - V) = 0.02$

Temporal slopes $\alpha_1 = 0.67 \pm 0.02$  $\alpha_2 = 2.5 \pm 0.03$ and $t_j = 0.86 \pm 0.03$

If $\nu > \nu_c$, $\alpha_2 \sim p$ but predicted $\alpha_1$ is steeper, not in agreement with observed one

GRB 030226 SED, Pandey et al. (2004)
Optically Dark GRBs

GRBs with no optical afterglows but having X-ray, radio afterglows

~ 40% of the afterglows are optically dark

Explanations

- Failure to image quickly and/or deeply enough
- Intrinsically dim bursts
- Absorption due to circumburst extinction
- High red shift bursts (optical absorption in Ly\(\alpha\) forest)
GRB 021211 afterglow, Optically dim burst

- Optically dim, \(~3\) mag fainter than GRB 990123
- Detected \(~90\) sec after the burst
- R band, single power law \(\sim 11\) min to 35 days with decay index \(\alpha \sim 1.1\)
- Compared with GRB 000630 (Fynbo et al, 2001)
  GRB 020224 (Berger et al, 2002)
- Detected R \(\sim 23\) mag, one day after the burst and similar temporal decay
- It would have been classified as optically dark burst in absence of rapid follow-up
SED of GRB 021211 afterglow

In this case, at Δt = 0.13, 0.77 and 0.86 day and β = 0.66±0.34, 0.61±0.09 and 0.53±0.15, E(B–V) = 0.028

No jet-break signature was observed

νc lying below optical frequencies
Variability in afterglow LC

Variability (?)

Density fluctuations
- Clumpy ISM
- Variable Stellar wind

Energy fluctuations
- Velocity effect (Refreshed shock model)
- Angular effect (Patchy shell model)
Variability in afterglow LC

- Density dominated fluctuations are effective for $\nu < \nu_c$
  - Produce only weak fluctuations
  - Can’t produce sharp changes in LC

- Energy variations will produce fluctuations below & above $\nu_c$

- Refreshed shock model (Produce random fluctuations)

- Patchy shell model (Hot or Cold spots in the jet)
  Intrinsic angular structure
  As the blast-wave decelerates, the angular size increases more than $1/\Gamma$, we see more and more jet structure.
Superimposed variability in the afterglow LCs

- Deviation from simple power-law i.e.
- Bumps & Wiggles in the light curve or achromatic flux variations

GRB 000301C (Sagar et al. 2000), GRB 021004 (Pandey et al. 2003)
GRB 030329, Variability with SN-bump

- First evidence GRB 980425/ SN 1998bw (Galama et al., 1998)
- Unambiguous supernova signature was detected for GRB 030329 by (Stanek et al., 2003)
- Late time red-bumps, weeks after the GRB show change in colour from the afterglow in GRB 970828 (Reichart et al., 1999), GRB 980326 (Bloom et al., 1999), GRB 011121 (Garnavich et al., 2002), GRB 020405 (Price et al., 2003) and GRB 021211 (Della Valle et al. 2003) too.

Recently, Resmi et al. (2005) modeled the BVRI data of GRB 030329 in terms of two-component jet model by Berger et al. (2003) fitted early ≤ 1.5 day optical, X-ray data as ultra-relativistic $N_A$ component and > 1.5 day optical and radio data using mildly relativistic $W_A$ component.
Monitored from 3 hours to 33 days after the burst

UBVI, earliest observations

Peculiar afterglow light curves with overlapped variability and SN 2003dh contribution
GRB 030329/SN 2003dh

Deviation from a broken power-law
Phases of re-brightening
Later part dominated by SN 2003dh contribution

(B-R) grows redder, (V-I) grows bluer, after 6 days, typical for a SN evolution
GRB 030329/ SN 2003dh

Two-jet model, NAJ for < 1.5 day
WAJ for > 1.5 data

R-band residuals, show step-like profile, expected from Patchy shell
Model, re-freshed shocks
Broad-band afterglow modeling

- Test for the synchrotron fireball model predictions
- Infer spectral break frequencies ($\nu_a, \nu_m, \nu_c$)
- Important to know the physical parameters $n, \varepsilon_e, \varepsilon_b, p, \theta, E_{52}$ (afterglow kinetic energy) of the burst
- Intrinsic extinction to host reveals conditions in the surrounding media
- Non-relativistic evolution of the fireball
- Test for other underlying mechanisms like Inverse-Compton scattering
Broad-band afterglow modeling

- Use simple fireball synchrotron ISM model (UJ) predictions
- Use break-frequencies and peak flux evolutions in fast, slow cooling cases
- Also include non-relativistic evolution of the fireball
- Use Granot Sari (2002) approach to get the modeled flux
- Used $\chi^2$ minimization method to get a fitted model parameters
- Model parameters are $E_{52}$, Peak flux, $n$, $p$, $E(B-V)$, 3 break frequencies, $t_j$, $t_{nr}$
- Calculation of physical parameters after inverting the model equations given in standard papers like (Wijers & Galama 1999, Rhoads 1999)
we modeled the 10 GHz, BVRI light-curve and SED at $\Delta t = 1.37$ and 5.67 day with following parameters including intrinsic extinction

Using derived break frequencies $\nu_a \sim 2.1$ GHz, $\nu_m \sim 2.5 \times 10^{14}$ Hz & $\nu_c \sim 3.3 \times 10^{16}$ Hz
Jet break time $t_j = 8.8$ day and $p = 2.27$, k-corrected energy $E_{52} = 4.6$, $e_e = 0.1$, $e_b = 0.01$ and total extinction $E(B-V) = 0.20$ in the burst direction.

Data points used 596, $t_{nr} \sim 108$ day, $n \sim 45$ atoms/cc
Broad band afterglow modeling
Broad band afterglow modeling

Using derived break frequencies \( \nu_a \sim 1.1 \text{ GHz}, \nu_m \sim 5.1 \times 10^{11} \text{ Hz} \& \nu_c \sim 5.7 \times 10^{14} \text{ Hz} \), \( t_j = 6.6 \text{ day} \), \( p = 2.27 \), excluded 3 - 4.3 day data from the fit, k-corrected energy \( E_{52} = 0.11, \epsilon_e = 0.01, \epsilon_b = 0.09, n \sim 0.001 \), at 8.46 GHz, 23 mJy Host contribution added
Broad band afterglow modeling

- BVRI, optical data,
  Galactic E(B-V)=0.022 mag
  Intrinsic extinction = 0.26 mag

- Needs Inverse-Compton effect with
  Synchrotron to explain the high frequency

- Used Additional parameter $C = \varepsilon_e / \varepsilon_b$

- Using derived break frequencies $\nu_a \sim 20.0 \text{ GHz}$,
  $\nu_m \sim 6.6 \times 10^{13} \text{ Hz}$ & $\nu_c \sim 8.8 \times 10^{12} \text{ Hz}$
  Jet break time $t_j = 2.1 \text{ day}$ and $p = 2.3$, $n \sim 8.77$
  k-corrected energy $E_{52} = 4.6$, $\varepsilon_e = 0.1$, $\varepsilon_b = 0.01$
  Inverse-Compton dominated Synchrotron gives better fit to the high frequency data
Broad band afterglow modeling

Modeled Radio and X-ray afterglow light curves of GRB 000926
Optical afterglow observations of GRBs (LCs and SEDs) are explained in terms of ISM jet model predictions, based on the afterglow LCs and SEDs.

Most of the afterglow light curves can be well explained in terms of jetted outflow, constraining total output energy.

K-corrected, jetted output energy of the GRBs falls in the range of standard energies clustered around $1.3 \times 10^{51}$ ergs.
Explanation/Energetics

**Modeled energy is in the range of the narrow clustering of $\sim 10^{51}$ erg**

(Frail et al., 2001, Bloom et al., 2003)
Results

- GRB 021211 afterglow observations show, Dark bursts might be just the optically dim bursts, rapid and deep follow up is needed to explore the fact.
- Overlapped variability in the afterglow light curve, indicate towards complex structure surrounding bursts.
- Observed intrinsic extinction in the burst direction shows GRBs to occur in gas rich region of the host galaxies.
- Optical data in combination with other frequencies, constrain the break frequencies, physical parameters using the afterglow models (ISM).
- Observed complex afterglow light curve of GRB 030329/ SN 2003dh strengthening the GRB progenitors as collapse of massive stars.
Need to know…

- Jet structure  *UJ or USJ, Polarization in afterglows*
- Progenitors  *Collapsars or Compact-binary mergers*
- Underlying total output energy, non-electromaganetic ?
- GRB-SN connection  *Supernova model*
- Types of GRBs  *short-duration afterglows*
THANKS...
GRB 010222, afterglow LCs

- $\alpha_1 = 0.74 \pm 0.05$, $\alpha_2 = 1.35 \pm 0.04$, $t_j = 0.7 \pm 0.07$ day
- Spectral index $\beta$ and temporal indices can be explained as sideways expansion of the jet
- Harder electron energy index $p < 2$ is needed to explain it, as modeled by Bhattacharya D. (2001)
- GRB 000301c is another example modeled with non-standard value $p < 2$, Panaitescu & Kumar (2001)
GRB 010222, afterglow SEDs

In this case, at $\Delta t = 0.35$, $0.77$ and $9.13$ day and $\beta = 0.61 \pm 0.02$, $0.83 \pm 0.13$ and $0.75 \pm 0.02$, $E(B-V) = 0.023$

$v_m$ lie in millimeter region and $v_c$ between optical and millimeter.