Gamma Ray Bursts and Their Afterglows

A New Chapter in Radio Astrophysics

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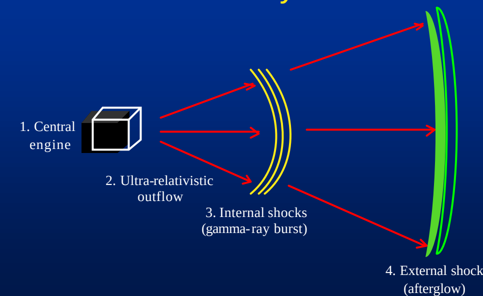
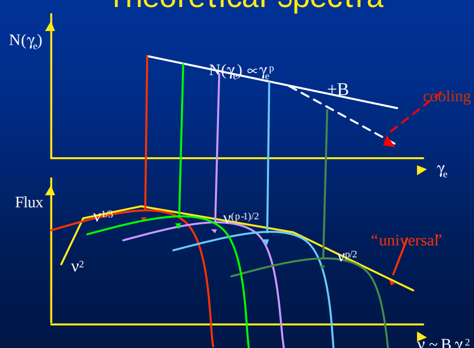
The New Radio Universe

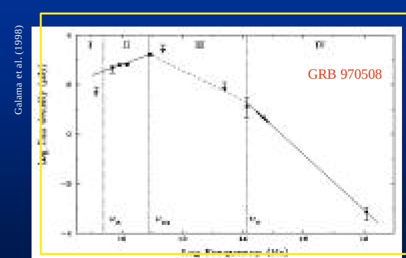
A Gamma-Ray Burst in Four Easy Pieces



Theoretical Spectra



Observations vs Theory



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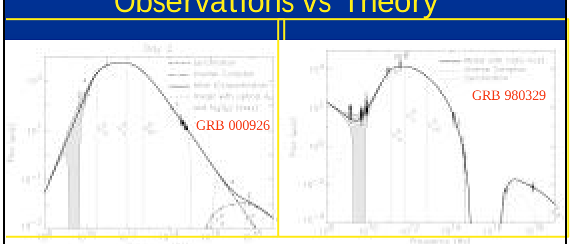
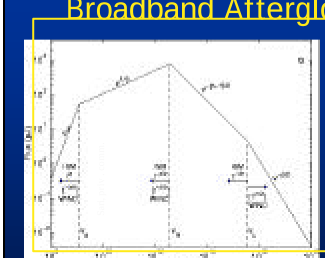


Good agreement between theory and observations

Broadband Afterglow Spectrum



Use the afterglow light curves and spectra to infer:
- the total energy of the outflow
- the geometry of the outflow
- the density structure of the circumburst medium

Inferring Physical Parameters from the Observed Spectra

We observe: ν_a ν_m ν_c F_m

We infer: R γ_{min} B N

$n \sim N/R^3$

$A \sim N/R$

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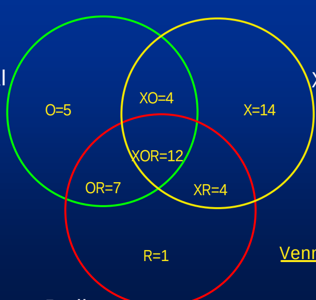
Talk Outline

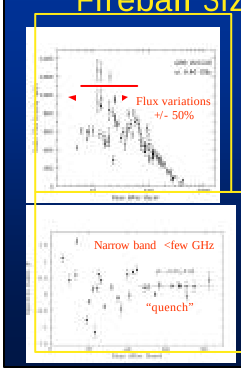
- The Radio Afterglow Sample
  - detection statistics
- Fireball size and relativistic expansion
- Energetics
  - beaming angles and broadband modeling
  - Sedov-Taylor estimates
- Circumburst Environment
  - density indicators
  - dark bursts

The First Five Years: 1997-2001



Venn Diagram

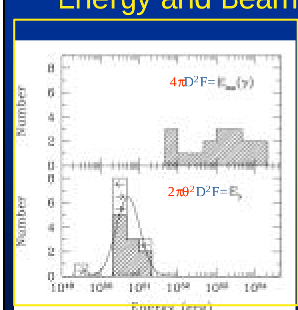
Fireball Size and Expansion



- Rapid (~hrs), narrow-band (~GHz) flux variations
  - diffractive scintillation (Goodman 1997)
  - size at 1 month ~10^{17}cm (3 uas)
  - superluminal expansion
- Rising spectrum ν^2 at low frequencies (Katz & Piran)
  - synchrotron self-absorption
  - size at 1 month ~10^{17}cm

An early confirmation of the fireball model

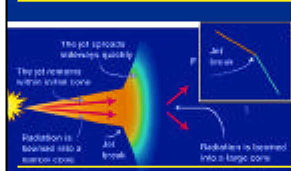
Energy and Beaming Corrections



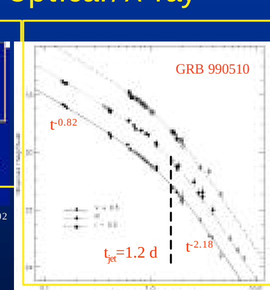
Frail et al. (2001)

- Use isotropic gamma-ray energy as a proxy for total energy in outflow
- Need to correct for the geometry of the outflow
- Signature of a jet is an achromatic break in the light curve

Jet Signatures: Optical/X-ray



Piran, *Science*, 08 Feb 2002

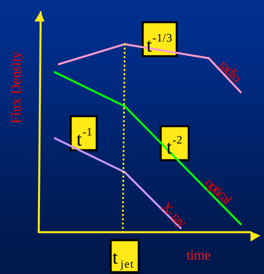


Harrison et al. (1999)

Achromatic breaks

- edge of jet is visible
- lateral expansion

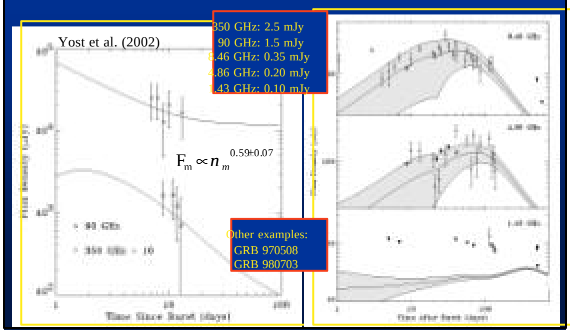
Jet Signatures: Give me a break!



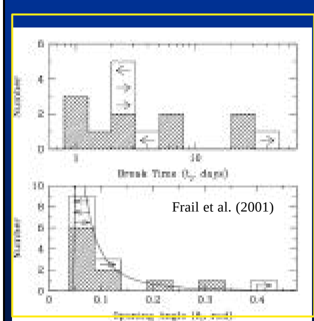
- The jet signature in radio is different
  - rise → decay
  - "Peak flux cascade"

$$\text{ISM, iso: } F_m \propto \nu_m^{0}$$
$$\text{ISM, jet: } F_m \propto \nu_m^{1/2}$$
$$\text{Wind, iso: } F_m \propto \nu_m^{1/3}$$
$$\text{Radiative: } F_m \propto \nu_m^{0.08} \quad (\epsilon_e = 0.1)$$

Peak Flux Cascade: GRB 980329



Jets Breaks and Opening Angles



- Determining the true gamma-ray energy requires measuring achromatic breaks over a wide range of timescales
- The different jet signature in radio bands gives added confidence
  - X-ray: flares
  - Optical: host-dominated, density fluctuations, lensing, refreshed shocks, wide angle jets

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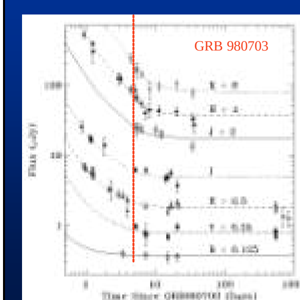

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Energy and Circumburst Density

- Criticism: Geometry-corrected gamma-ray energy depends on circumburst density

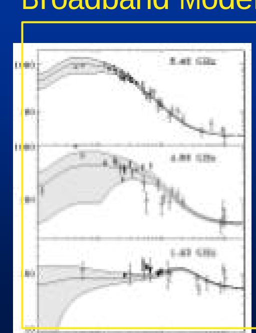
$$E_\gamma \propto \left[\frac{t_{jet} E_{\gamma,iso}}{1+z}\right]^{3/4} n_o^{1/4} \eta_\gamma^{1/4}$$

  but $10^{4} \leq n_o \leq 10^{6}\ cm^{3}$

- Hydrodynamic evolution of the blast-wave depends strongly on:
  - total energy in outflow, geometry of outflow, and density structure of circumburst medium

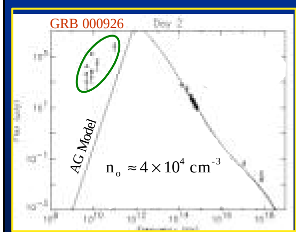
…broadband afterglow modeling is the key

Broadband Modeling: GRB 980703



- Frail et al. (2002) have carried out recent modeling of all radio, optical, NIR and X-ray data
  - $n_o \approx 27\ cm^{3}$

GRB Environments: GRB 000926



Harrison et al. (2001) vs Piro et al (2001)

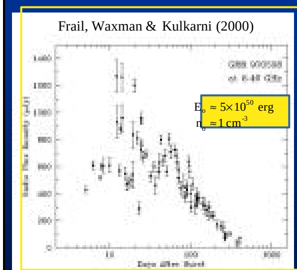
$n_o \approx 30\ cm^{-3}$ vs $n_o \approx 4\times10^4\ cm^{-3}$

- Radio AGs rule out extreme densities and yield $n_o \approx 10\ cm^{-3}$
- Most GRB AGs can be described by a jet-like outflow in a constant density medium
- In order to conclusively link GRBs and massive stars we must see the wind signature
  - Radio measurements are sensitive to both the absolute value of the gas density and its radial dependence

(i.e., $r\ (r) \propto r^{-2}$)

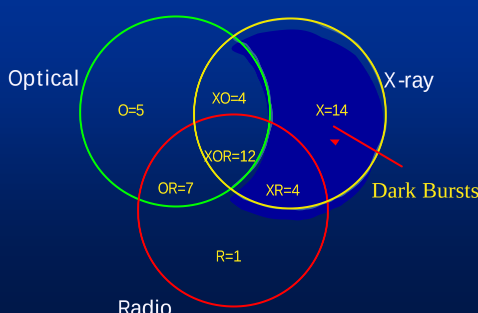
Fireball Calorimetry

Frail, Waxman & Kulkarni (2000)



- Long-lived radio afterglow makes a transition to NR expansion
  - no geometric uncertainties
  - can employ robust Sedov formulation for dynamics
  - compare with equipartition radius and cross check with ISS-derived radius
- Different methods agree

The Population of Dark Bursts



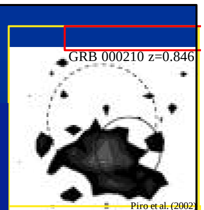
How Do You Make a Dark Burst?

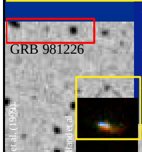
- Intrinsically faint afterglow
  - low energy, fast decay, etc.
- Dust extinction
  - Dust and gas along the line-of-sight or within the circumburst environment
- High redshift
  - Absorption by Ly-alpha forest for z>5
  - predictions of up to 50% of all bursts

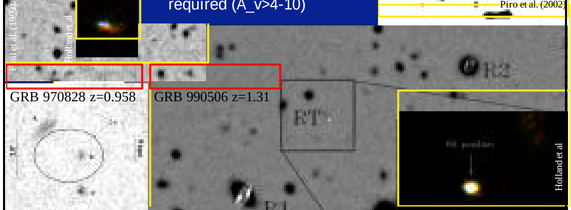
…Need a sample of well-localized bursts

X-ray/Radio Dark Bursts

- host galaxies are at modest redshifts (no z>5 candidates)
- X-ray/radio predict bright optical afterglow (not faint)
- significant extinction required (A_v>4-10)

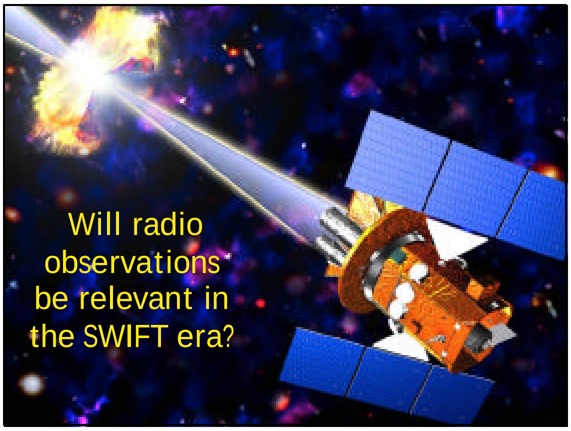






Emerging Picture

- a gamma-ray burst is the result of a catastrophic release ~10^51 erg of energy
- the resulting outflow expands (highly) relativistically and has a jet-like geometry
  - there is a distribution of opening (or viewing) angles
- the explosion occurs in a gas-rich environment
  - the measured circumburst density is ~10 cm-3
  - there is some evidence for progenitor mass-loss
- the most likely progenitor of long-duration GRBs are massive stars (aka collapsar)



Conclusions

Radio observations of afterglows have an important (and sometimes unique) role to play

- Can “resolve” the outflow via interstellar scintillation
- Samples portion of afterglow spectrum which is vital for constraining the physical parameters of the fireball
- Radio afterglow can “see” wide-angle jets
- Long-lived radio afterglow can capture NR transition
- Not sensitive to dust obscuration (dusty hosts), Lyman breaks (z>5), time of day, weather, lunar phase