GRB Jets – Some open Questions

Tsvi Piran
Caltech & Hebrew U.

- Ehud Nakar, Caltech
- Avishay Gal Yam, Caltech
- Derek Fox, Caltech
- Ramesh Narayan, Harvard
- Pawan Kumar, Texas
- Dafne Guetta, Rome
- Eli Waxman, Weizmann
- Jonahtan Granot, Stanford
- Yonatan Oren, HU

OUTLINE

- Observations
- The Fireball Model
- Open Questions
  - Recent News
    - The hyper-giant flare from SGR 1806-20
    - The Short GRB 050509
    - The Amati ($E_{peak} - E_{iso}$) relation
  - Jets
    - Evolution
    - Structure UJ vs USJ
    - Orphan Afterglows
  - The Frail relation and energetic (wide jets refreshed shocks).

Piran, 2005
Rev. Mod. Phys 76, 1143-1210

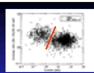
Properties

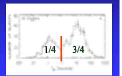
- **1 burst in 2×10^7 years/galaxy (3×10^5 years/galaxy with beaming**

Compton GRO with BATSE

Properties

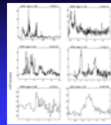
- Duration 0.01-1000s
  Two populations (long and short)





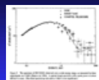
Properties

- Rapid variability (less than 10ms)



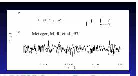
Properties

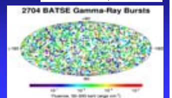
- ~10-2000keV photons
  (non thermal spectrum)
  A very high energy tail. Definitely up to GeV. Possibly up to 500GeV?)



Properties

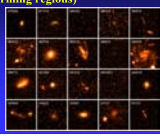
- Cosmological





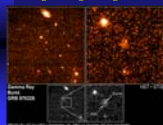
Properties

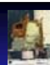
- Host Galaxies (burst with star forming regions)



Properties

- Long lasting afterglow

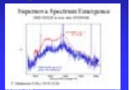




BeppoSAX

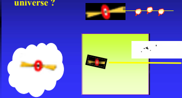
Properties

- SN association –
  Predicted – (Paczynski, Woosley)
  Confirmed – Galama et al., Bloom et al., Staneck et al., Hjorth et al.,



GRBs are good for many thing:

- Determining the high redshift history of the universe ?



GRBs are ~~good~~ bad for many thing:

- Destroy Life on Earth (mass extinction) ??

GRBs are good for many thing:

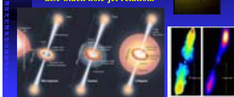
- Creat Life on Earth (trigger planet formation)?

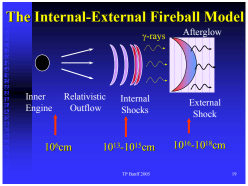
GRBs are good for many thing:

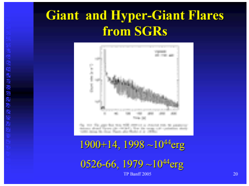
- Measuring quantum gravity effects ?

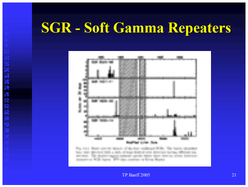
GRBs are good for many thing:

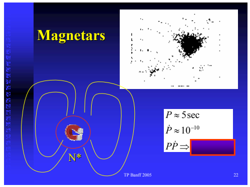
- Determining the nature of relativistic jets and the disc-black hole-jet relation.

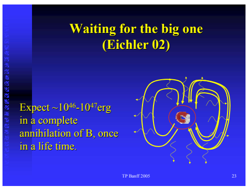


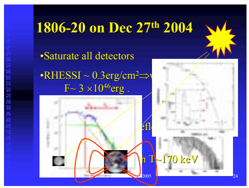

The Internal-External Fireball Model
γ-rays
Afterglow
Inner Engine
Relativistic Outflow
Internal Shocks
External Shock
10^6cm
10^{13}-10^{15}cm
10^{16}-10^{18}cm
TP Banff 2005
19


Giant and Hyper-Giant Flares from SGRs
1900+14, 1998 ~10^{44}erg
0526-66, 1979 ~10^{44}erg
TP Banff 2005
20


SGR - Soft Gamma Repeaters
TP Banff 2005
21

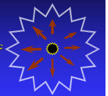

Magnetars
N*
$P \approx 5$sec
$\dot{P} \approx 10^{-10}$
$P\dot{P} \Rightarrow$
TP Banff 2005
22


Waiting for the big one (Eichler 02)
Expect ~10^{46}-10^{47}erg in a complete annihilation of B, once in a life time.
TP Banff 2005
23


1806-20 on Dec 27th 2004
•Saturate all detectors
•RHESSI ~ 0.3erg/cm^2⇒
F~ 3 ×10^{46}erg .
h T~170 keV
2005
24

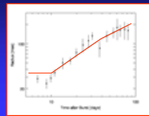
Radio Afterglow!

- After one week
  - ~50 mJy at 8.47Ghz
  - Extended~30-180 masec
- ⇒Relativistic ejecta
  - E>10^{43}erg (10^{46} erg?)

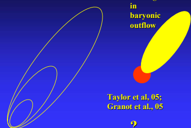


The flare and the afterglow correspond to a pure radiation fireball + (separate) baryonic component (Nakar, TP, Sari, 05, Granot et al., 05)

Relativistic Motion of the Afterglow!



Taylor et al., 05



Taylor et al, 05;
Granot et al., 05

?

Are Short GRB Extragalactic Hyper-Giant Flares from SGRs?

- E~3 ×10^{46}erg can be detected to ~50Mpc.
- 1 burst per 30 years

The expected rate (at BATSE sensitivity ~10^{-7}erg/cm^2) is comparable to BATSE's detection rate of ~170 bursts per year?

Are Short GRB Extragalactic HyperGiantFlares from SGRs?

NO!

Nakar, Gal-Yam, TP, Fox, 05

?

Assuming that the progenitors of short GRBs trace some kind of light (UV [star formation], blue or red) we set limits of

>10^{48}-10^{49} erg

on the fluences of seven short GRBs.

This is a conservative limit that assumes that all seven GRBs are located at very dim galaxies (<0.01L$_*$).

A less conservative limit is ~10^{50} erg.

Additional Evidence

- $\langle V/V_{max} \rangle \sim 0.4$
- No correlation with LSS (at >100Mpc there will be some induced correlation)
- Spectrum (Lazzati et al., 05)

A possible resolution: SGR 1806-20 is nearer (Cameron et al., 05, Nakar et al., 05)

The Hard Short Burst GRB 050905b

- Duration 30 msec !
- Hard spectrum
- X-ray afterglow observed after ~200 sec

XRF position – no clear host

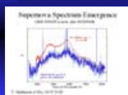
Elliptical Galaxy and a cluster at z=0.22

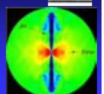
Much Ado about Nothing

- Unknown parameters : d (z) , E_a/E_γ , n
- Simplest fit: $E_a/E_\gamma \sim 1$, n~1
  - In the elliptical at z=0.2 $E_\gamma \sim 10^{49}$ erg
  - At z~1.8 $E_\gamma \sim 10^{50.5}$ erg
- $E_a/E_\gamma \sim 30$, $n \sim 10^{-3}$ (in the cluster at z=0.2). E_a/E_γ fits the mini-jets of Nakamura et al. but no SN!
- $E_a/E_\gamma \sim 1000$, $n \sim 10^{-6}$ (in the IGM).

For long GRBs $E_a \sim E_\gamma \sim 10^{51}$erg

Collapsar - long GRBs
(Woosley, Paczynski)

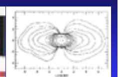




In star forming regions within regular spiral galaxies.

Neutron Star Mergers- short GRBs ?
(Eichler, Livio TP, Schramm 89)

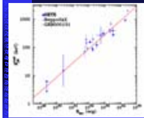
Rosswog et al , 04



Davies et al , 94

In elliptical galaxies.
Possibly kicked out from small galaxies.
Expect less energy than in a Collapsar $\sim 10^{49-50}$erg

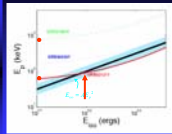
The Amati E_p-E_{iso} relation



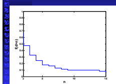
Amati et al., 2001
Lamb et al., 2003

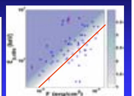
$$E_{iso} = 1^{+1}_{-0.5} \times 10^{48} \left(\frac{E_p}{1keV} \right)^2 ergs$$

A test for bursts with no redshift (Nakar & TP 04)



A sample of 61 BATSE bursts with known E_p from Band et al.,(1993) and Jimenez et al., (2001):

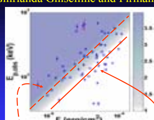


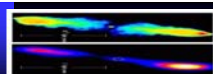


Ghirlanda Ghiselline and Firmani 05: "with the correct spread" BATSE bursts are consistent with the Amati Relation.

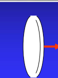
Δ/σ	Observed fraction with a larger Δ/σ	Expected fraction with a larger Δ/σ	Probability to find the observed fraction
0	84%	69%	10^{-}[illegible]
1	58%	38%	10^{-}[illegible]
2	27%	4.7%	10^{-}[illegible]
3	7.7%	0.62%	10^{-}[illegible]

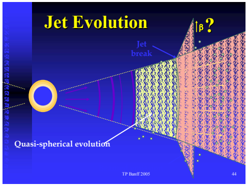
Ghirlanda Ghiselline and Firmani 05:

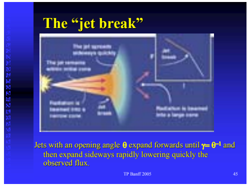


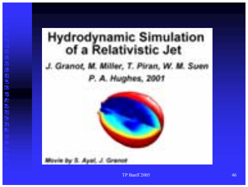


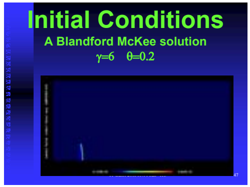
- For most astronomical jets
  T (duration) >> R/c.
- For GRBs
  T (duration) << R/c
- A better terminology would be "Flying Pancakes".

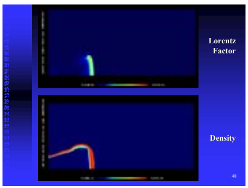


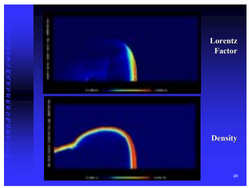

Jet Evolution
β ?
Jet break
Quasi-spherical evolution
TP Banff 2005
44

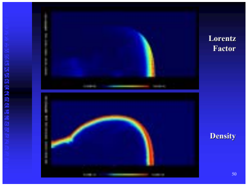

The “jet break”
Jets with an opening angle θ expand forwards until γ= θ⁻¹ and then expand sideways rapidly lowering quickly the observed flux.
TP Banff 2005
45

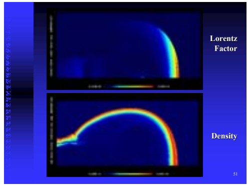

Hydrodynamic Simulation of a Relativistic Jet
J. Granot, M. Miller, T. Piran, W. M. Suen
P. A. Hughes, 2001
Movie by S. Ayal, J. Granot
TP Banff 2005
46

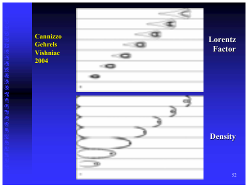

Initial Conditions
A Blandford McKee solution
γ=6 θ=0.2
47

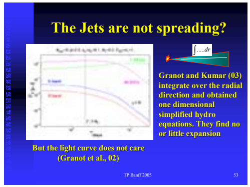

Lorentz Factor
Density
48

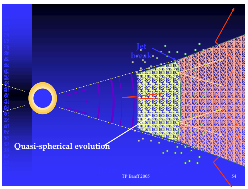

Lorentz Factor
Density
49

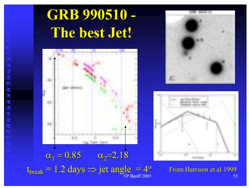

Lorentz Factor
Density
50


Lorentz Factor
Density
51


Cannizzo
Gehrels
Vishniac
2004
Lorentz Factor
Density
52

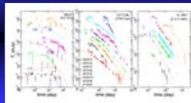

The Jets are not spreading?
Granot and Kumar (03) integrate over the radial direction and obtained one dimensional simplified hydro equations. They find no or little expansion
But the light curve does not care (Granot et al., 02)
TP Banff 2005
53


Jet break
Quasi-spherical evolution
TP Banff 2005
54


GRB 990510 - The best Jet!
α1 = 0.85
α2=2.18
tbreak = 1.2 days ⇒ jet angle = 4°
From Harrison et al 1999
TP Banff 2005
55

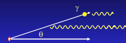
Comparision with Observations

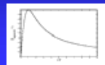
980519, 990123, 990510, 991208, 991216
000301c, 000926 & 010222



Panaitescu & Kumar, 2001

Superluminal Motion Point Source

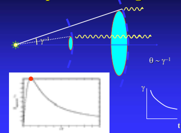




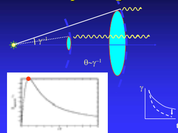
$$\frac{v_{ap}}{c} = \frac{\beta \sin(\theta)}{1-\beta\cos(\theta)} \approx \frac{2\gamma}{\theta\gamma + 1/\theta\gamma}$$

Superluminal Motion Spherical Afterglow

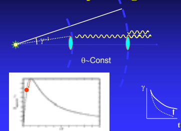
Oren, Nakar & TP 04



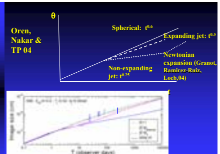
Superluminal Motion Expanding Jet



Superluminal Motion Non-expanding Jet



Oren, Nakar & TP 04



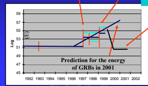
The Energy

971214

990123

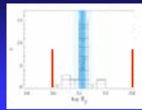
$E_\gamma = \frac{\theta^2}{2} E_{\gamma iso}$

GRB Jets



The energy is constant ~10^{51} erg

(Frail et al., 01; Panaitescu & Kumar 01)



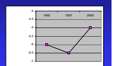
From Afterglow

$E_\gamma = \frac{\theta^2}{2} E_{\gamma iso}$

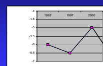
From GRB

From Bloom et al., 03

- The beaming correction:
  $\langle f_b^{-1} \rangle \sim 500$
  (Frail et al. 2002).



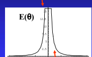
- The beaming correction:
  $\langle f_b^{-1} \rangle \sim 50$
  (Guetta TP Waxman 04).
- Rate:
  3 10^{-7}/ Gpc^3yr
  2.5 per 10^6yr/galaxy
  1 GRB per 4000 SNe

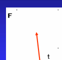


L
S

USJ- Universal Structured Jet vs. UJ – Uniform Jet

core



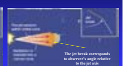


$E \sim \theta^{-2} \rightarrow E_{iso}\ \theta^2 \approx$ const

(Lipunov, Postanov & Prokhorov 01; Zhang & Meszaros 02; Rossi et al., 02)

Break at θ_{obs}~θ_{jet}

UJ vs. USJ

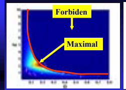


UJ

USJ

USJ vs. UJ – Why Do We Care?

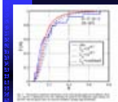
- Different processes within the "inner engine", USJ → Standard collimation, standard profile.
- USJ have about 10 times more energy.
- The rate of USJs is ~10 times smaller than the rate of UJs.

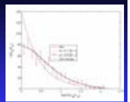


$d^2N/dzd\theta$ using the same assumptions, (Nakar Guetta, Granot 03)

$dN/d\theta$ (Perna et al., 03)

– A burst of hope

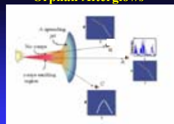




$L\theta^2$~Const

Guetta TP Waxman (03)

Orphan Afterglows

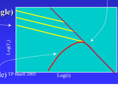


Observer A: a regular GRB.
Observer B: an on axis orphan afterglow.
Observer C: an off axis afterglow

The Universal Light Curve

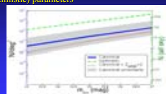
Granot, Panaitescu, Kumar & Woosley 02;
Nakar Piran & Granot 02

The realization that GRBs involve a constant amount on energy E_{tot} implies that GRB afterglows have a universal light curve after the jet break.



The Expected Detection Rate:

- 3 (60) orphans afterglow in a single whole sky snapshot with m_{lim}=23 in the R-band for our canonical (optimistic) parameters

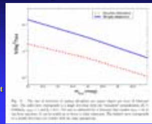


(Nakar, Piran & Granot 2002)

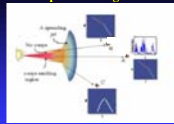
Totani & Panaitescu (2002) predicts an observation rate which is a factor of 60 larger than our canonical predictions and a factor of 3 above our optimistic prediction.

The Detection Rate per hour of telescope time

The rate increases with a lower limiting magnitude as the lower rate of events is compensated by the efficient coverage of large areas.



Orphan Afterglows



Observer A: a regular GRB.
Observer B: an on axis orphan afterglow.
Observer C: an off axis afterglow

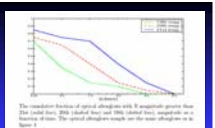
Wide Low γ Jets

(Nakar & TP 01, Berger et al., 03)

- BeppoSAX observations of xrfs put a strong limit on the energy in x-ray emitting matter (lower Γ) and γ-ray emitting matter (high Γ) $E_x/E_\gamma < 3$ (Nakar & TP 01).
- Optical and radio searches could put limits of lower Γ ejection.

Survey	Sensitivity erg/sec/cm²	Δt min	θ min	$t_{...}$ min	Expected events	Observed events	Bounding ratio
ROSAT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HEAO-1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ariel 5	[illegible]	[illegible]	[illegible]	prompt	[illegible]	[illegible]	[illegible]
BeppoSax WFC	[illegible]	-	-	prompt	[illegible]	[illegible]	[illegible]

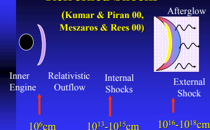
- BeppoSAX observations of xrfs put a strong limit on the energy in x-ray emitting matter (γ) and γ emitting matter (high γ) $E_x/E_\gamma < 3$ (Nakar & TP 01).



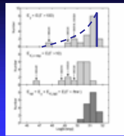
•Optical searches could put limits of lower γ ejection.

Refreshed Shocks

(Kumar & Piran 00, Meszaros & Rees 00)



Back to the Frail Relation:



The Frail Relation should be used as an upper limit that is utilized in the most efficient cases.

Berger et al., Nature, 2003

Summary

- Jets are an integral parts of GRBs.
- While the situation is "steady state" at the source, GRB jets are very different from other jets on large scales.
- Short GRBs are NOT Hyper-giant SGR flares. With more than 10^{49} erg we still wonder what they are.
- The single *Swift* short GRB is consistent with a binary neutron star merger taking place within an elliptical galaxy at z~0.2
- The total energy ejected in GRBs is rather constant but at times not all of it is of high quality (namely high Γ).
- BATSE GRBs (and possibly the first Swift GRB with a known redshift) do not satisfy the Amati relation.

The END