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SUMMER SCHOOL ON ASTROPARTICLE PHYSICS AND COSMOLOGY

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GAMMA RAY BURSTS

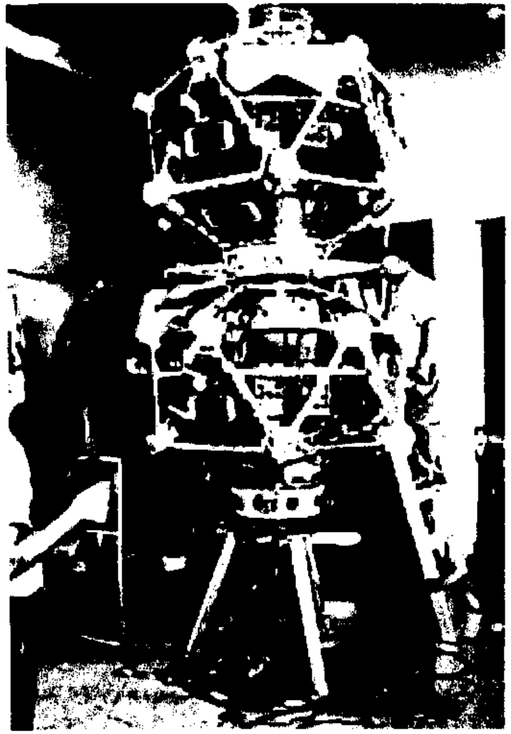
E. WAXMAN
Weizmann Institute
Rehovot
ISRAEL

Please note: These are preliminary notes intended for internal distribution only.

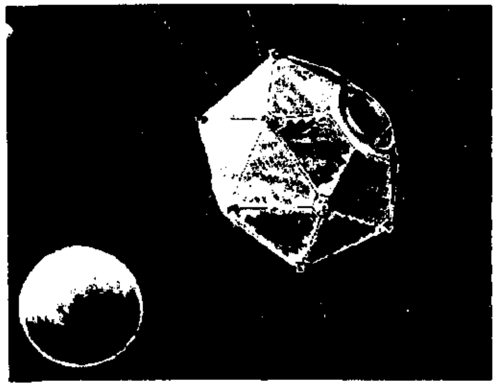
I. γ-ray observations

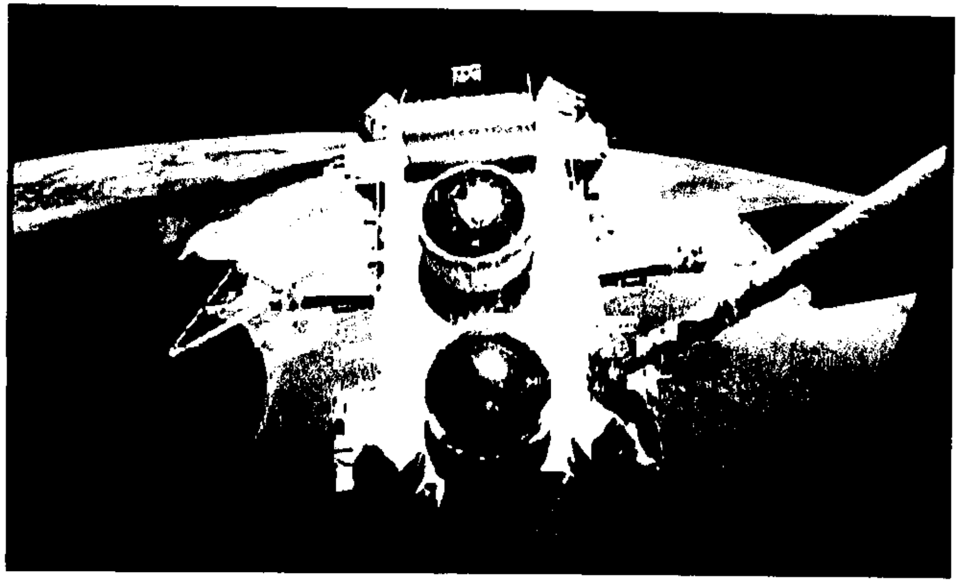
The discovery of Gamma-Ray Bursts

Review: G.J. Fishman & C.A. Meegan
ARAA 1995, vol. 33, p. 415



The VELA satellites
(1963 -)





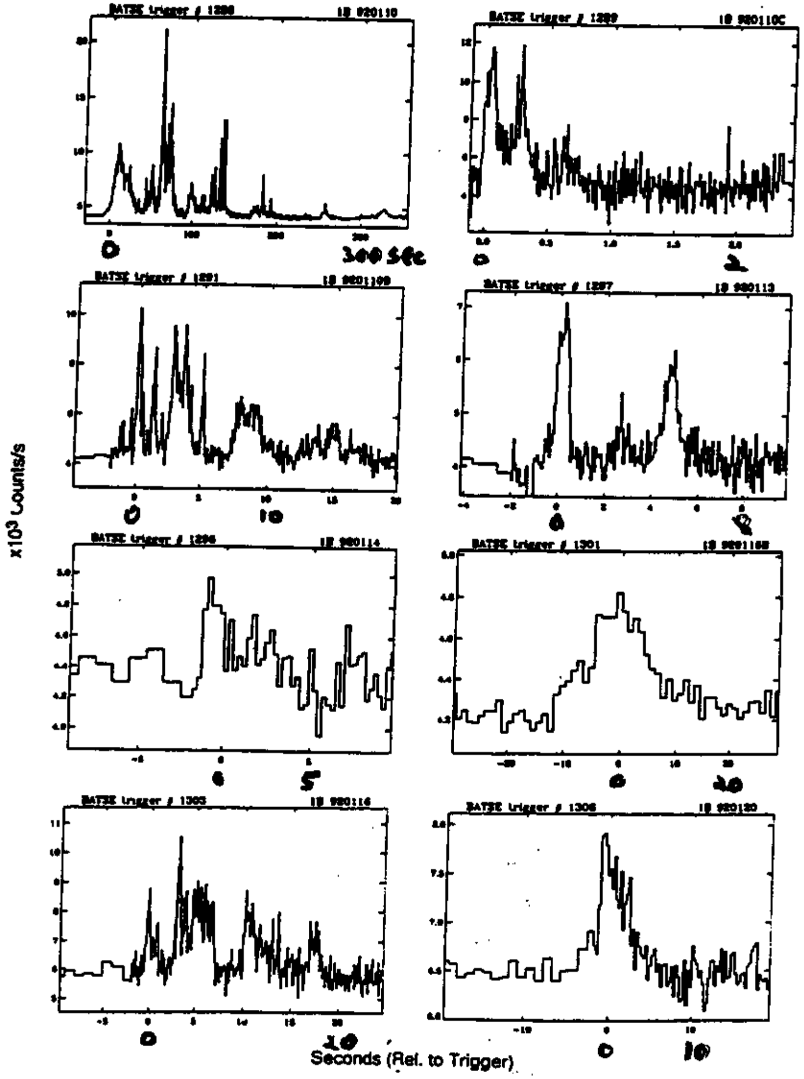
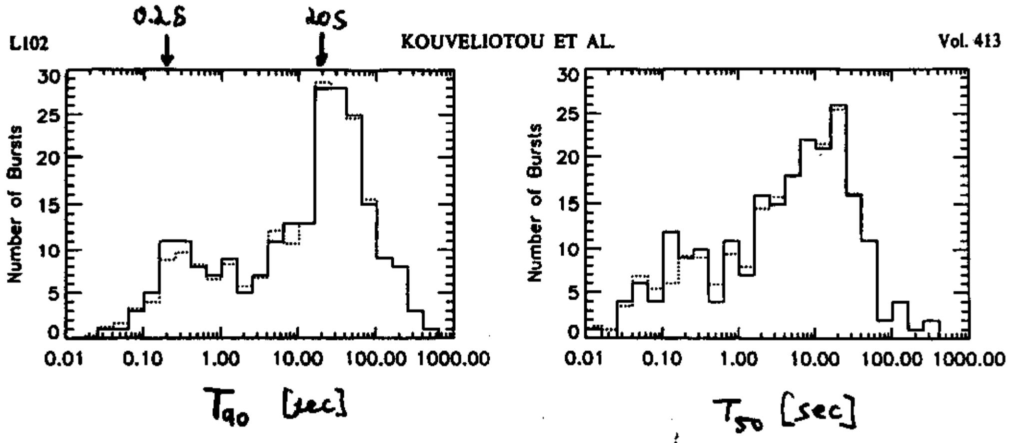


Figure 1 Sample page from the *First BATSE Catalog of Gamma-Ray Bursts* (Fishman et al 1994b), indicating the diversity in the time profiles, intensities, and durations of gamma-ray bursts.

Bimodal Duration Distribution



$$E^2 \frac{dN_\gamma}{dE}$$

$$\frac{dF_\gamma}{d\log E}$$

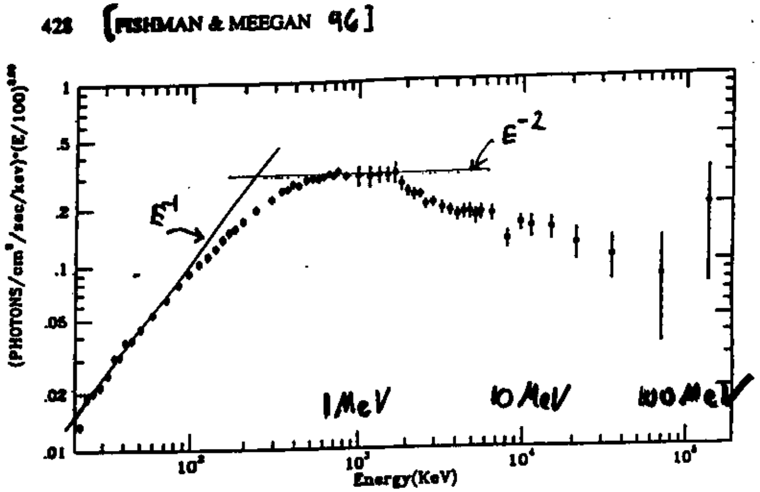


Figure 10 The spectrum of GB 910503, measured by all four experiments on the *Compton Gamma Ray Observatory* (Schaefer et al 1994d).

Variability

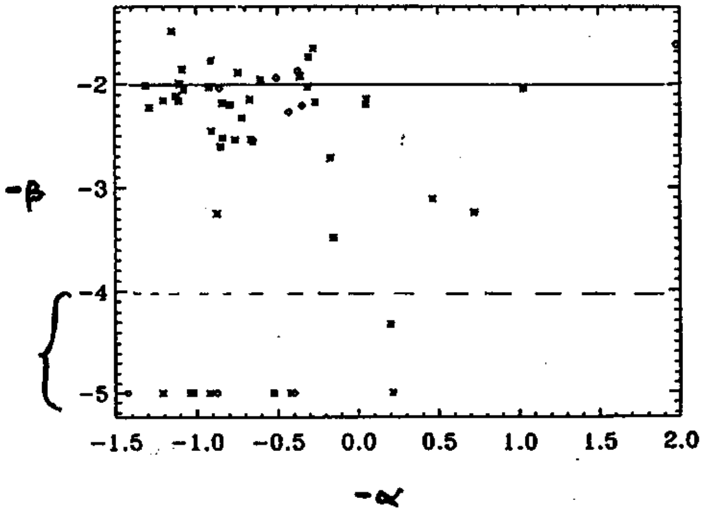
- Most GRB's show variability on shortest resolved BATSE time-scale: $\Delta t = 64\,ms$

- Some show variability on $\Delta t \sim 1\,ms$

Spectral Properties

[D. Band et al. 93, ApJ 413, 281]

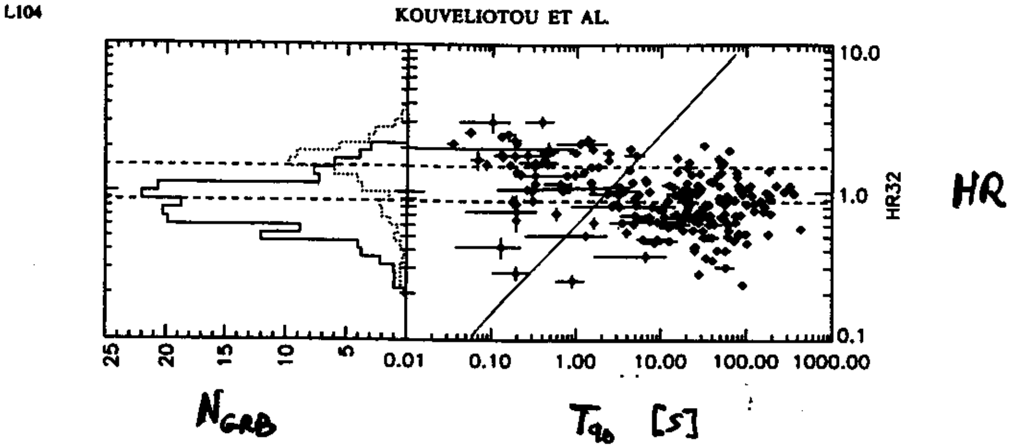
- Model: $$\frac{dN_\gamma}{dE_\gamma} \propto \begin{cases} \varepsilon_\gamma^{-\alpha} & \varepsilon_\gamma < \varepsilon_0 \\ \varepsilon_\gamma^{-\beta} & \varepsilon_\gamma > \varepsilon_0 \end{cases}$$
- Fit: $0.1\,MeV < \varepsilon_0 < 1\,MeV$
- (α, β):



≈20% : No High-Energy Emission

[Real ? Instrumental ?]

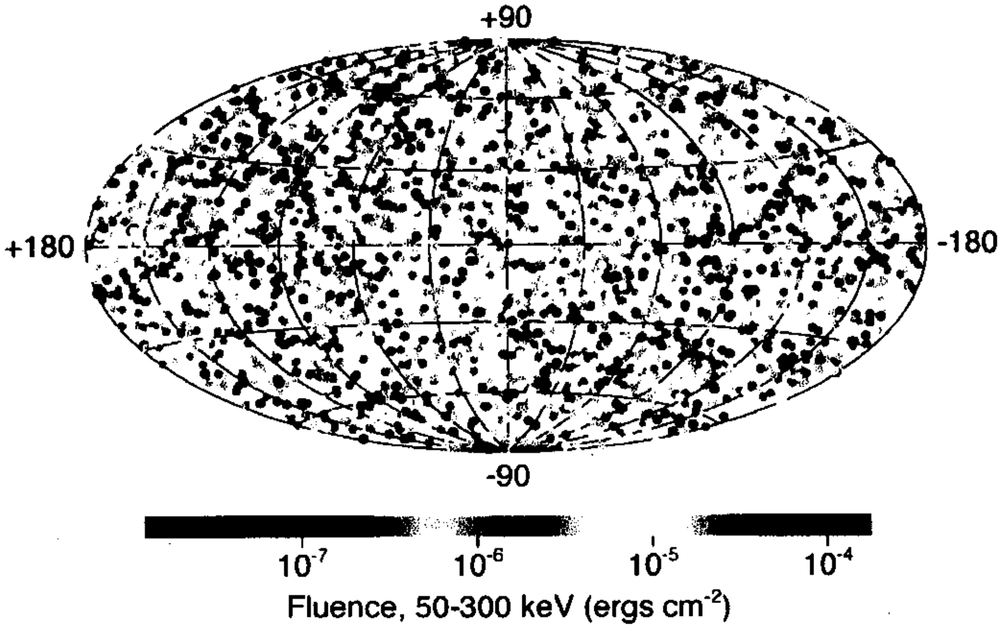
Spectrum - Duration Relation

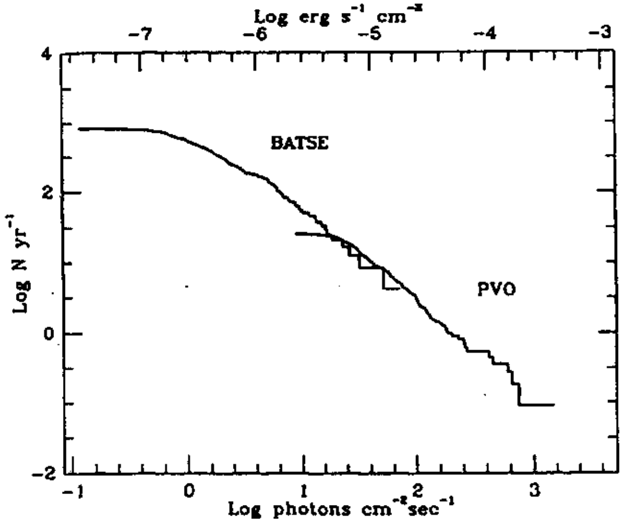


$$HR \equiv \frac{f[100-300\ keV]}{f[50-100\ keV]}$$

Rate and Flux distribution

2512 BATSE Gamma-Ray Bursts





I. γ-Observations: Summary

- Duration: $T_{90} \approx \begin{cases} 0.2\,s \\ 20\,s \end{cases}$

- Variability: Most show $\Delta t \sim 64\,ms$

  Some $\Delta t \sim 1\,ms$

- Spectrum: $\frac{dN_\gamma}{dE_\gamma} \propto \begin{cases} \varepsilon_\gamma^{-\alpha} & \varepsilon_\gamma < \varepsilon_0 \\ \varepsilon_\gamma^{-\beta} & \varepsilon_\gamma > \varepsilon_0 \end{cases}$

  $0.1\,MeV < \varepsilon_0 < 1\,MeV$, $\beta \approx 2$, α varies

  [No-high-energy-burst ? ~20%]

- Isotropic distribution

- $f = 10^{-4} - 10^{-7}\ erg/cm^2 \cdot s$

- $R \simeq 10^3\,/yr$

II. Implications: Fireballs

[Paczyński 86, ApJ 308, L43

Goodman 86, ApJ 308, L47]

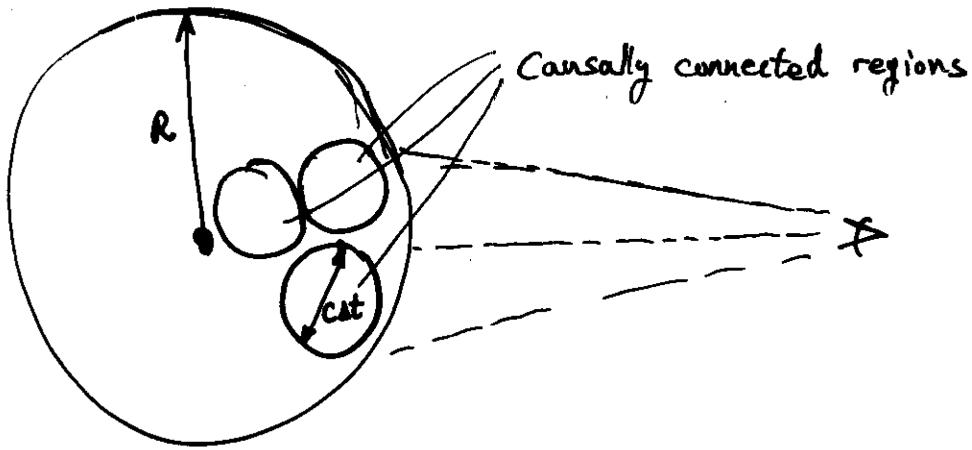
- Isotropy $\rightarrow$ Cosmological Sources

$$L = 4\pi d_L^2 f = 1.3 \cdot 10^{51}\, d_{L,28}^2\, f_{-6}\ \ erg/s$$

$$d_L = 10^{28} d_{L,28}\ cm, \quad f = 10^{-6} f_{-6}\ erg/cm^2 s$$

- $\Delta t \sim 1\,ms \rightarrow$ Small Source

$$r \lesssim c\Delta t \sim 3 \cdot 10^7\ cm$$



$N \sim \left(\frac{R}{c\Delta t}\right)^2$ independent regions

$\Rightarrow$ Flux variability:

$$\frac{\Delta f}{f} \sim \frac{1}{\sqrt{N}}$$

$\Rightarrow \quad \frac{\Delta f}{f} \sim 1 \iff N \sim 1 \iff R \sim c\Delta t$

I.1. The Energy Source

- Maximum source mass:

$$r_{BH} = \frac{2GM}{c^2} \Rightarrow M < \frac{c^2}{2G} r = 34\, r_7\, M_\odot$$

- $E_\gamma \approx 10^{53}$ erg $\leftrightarrow$ $Mc^2 = 1.8 \cdot 10^{54} \frac{M}{M_\odot}$ erg

Chemical Reaction: $\frac{E}{M} \sim \frac{1\,eV}{m_p} \sim 10^{-9}$

Nuclear Reaction: $\frac{E}{M} \sim \frac{1\,MeV}{m_p} \sim 10^{-3}$

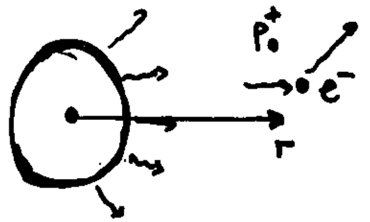
Gravitational Collapse of $\sim 1 M_\odot$ to Black-Hole:

$$E \sim Mc^2 \sim 10^{54} \text{erg} \frac{M}{M_\odot}$$

$$r_{BH} \sim 3 \cdot 10^5 \frac{M}{M_\odot} \text{ cm}$$

II.2. Relativistic Expansion

(1) The Eddington luminosity:



$$F_G = \frac{GM}{r^2} m_p$$

$$F_R = \frac{L}{4\pi r^2 c} \cdot \sigma_T$$

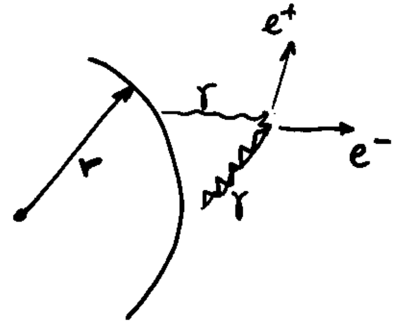
$F_R < F_G \Leftrightarrow$

$$L < L_{Edd.} = \frac{4\pi G M m_p c}{\sigma_T} = 1.3 \cdot 10^{38} \frac{M}{M_\odot} \ \text{erg/s}$$

Since $L \sim 10^{51} \frac{erg}{s} \gg L_{Edd}$

The source must expand relativistically!

(2) Optical Depth:



$$l_{\gamma\gamma} = \frac{1}{n_\gamma \sigma_T}$$

$$\tau_{\gamma\gamma} \approx n_\gamma \sigma_T r$$

$$L \approx 4\pi r^2 c \, n_\gamma \, \varepsilon_\gamma$$

$$\Rightarrow \quad \tau_{\gamma\gamma} \approx 10^{14} \frac{L_{51}}{r_7 \, \varepsilon_{\gamma, MeV}}$$

$\Rightarrow$ $\{\gamma, e^+, e^-\}$ fluid in thermal equilibrium

$$L \approx 4\pi r_0^2 \sigma T_0^4 \rightarrow T_0 \approx 1 \left(\frac{L_{51}}{r_{0,7}}\right)^{1/4} \text{MeV}$$

- Fluid expands, T drops,

$$n_{e\pm} = \frac{1}{\sqrt{2}\,\pi^{3/2}} \left(\frac{m_e T}{\hbar^2}\right)^{3/2} e^{-m_e c^2 / T}$$

for $T \ll m_e c^2 \sim T_0$ photons escape.

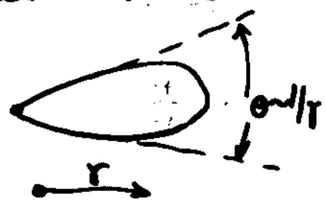
(3) Fireball evolution:

- Cooling:

Plasma Frame

Isotropy, $\varepsilon_\gamma = \varepsilon_\gamma^{ob}/\gamma$

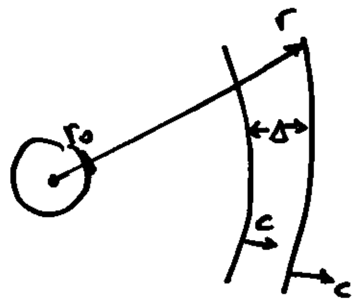
observer frame



ε_γ^{ob} Constant

$$\varepsilon_\gamma \approx T \propto 1/\gamma \quad ; \quad T \ll T_0 \Rightarrow \gamma \gg 1$$

- Shell:



$$\Delta \approx \text{Const.} \approx r_0$$

Evolution Equations

- Neglect $e^\pm$ in e.o.s. [$e^{-m_e c^2/T}$]

$$S = V(e+p)/T \quad , \quad p = \tfrac{1}{3} e \propto T^4$$

- Entropy conservation:

$$4\pi r^2 \cdot \gamma r_0 \cdot T^3 = \text{Const.}$$

Energy Conservation:

$$4\pi r^2 \cdot \gamma r_0 \cdot \gamma T^4 = \text{Const.}$$

$$\Rightarrow \quad \gamma = r/r_0$$

$$T = T_0 \left(r/r_0\right)^{-1}$$

- Photons escape at $T/m_e c^2 \approx 0.05$

! Thermal Spectrum, in contradiction with $\frac{dN_\gamma}{dE_\gamma} \propto E_\gamma^{-2}$.

(4) Adding Some Baryons:

$M, \quad \eta \equiv E/Mc^2 >> 1$

- $\gamma \propto r$ Until:

  [a.] Photons escape, $\tau_T < 1$

  or [b.] $E_{phot} \to E_K$, $\gamma = \frac{r}{r_0} = \eta$

- Thomson Optical Depth:

$$\tau_T = \gamma r_0 n_e \sigma_T = \gamma r_0 n_p \sigma_T$$

$$\frac{L}{\eta m_p c^2} = 4\pi r^2 \cdot c \cdot \gamma n_p$$

$$\Rightarrow \tau = \frac{\sigma_T L / \eta m_p c^2}{4\pi r_0 c} \gamma^{-2}$$

- $$\eta_* \equiv \left(\frac{\sigma_T L / m_p c^2}{4\pi r_0 c}\right)^{1/3} = 10^4 \left(\frac{L_{52}}{r_{0,7}}\right)^{1/3}$$

$$\gamma_{final} = \begin{cases} [a.] \ \eta_* & \text{if } \eta \geq \eta_* \\ [b.] \ \eta & \text{if } \eta < \eta_* \end{cases}$$

! $\eta_* = 10^4 \leftrightarrow M = 5 \cdot 10^{-6} E_{53} M_\odot$

$\Rightarrow$ If $M > 10^{-5} M_\odot$ $E_{phot.} \longrightarrow E_K$

$\Rightarrow$ No radiation observed.

[Paczyński 90, ApJ 363, 218

Shemi & Piran, 90, ApJ 365, L55]

Conclusion: • Source energy converted to kinetic energy of bargons.

- At $r \gg \eta r_0 \gg r_0$:

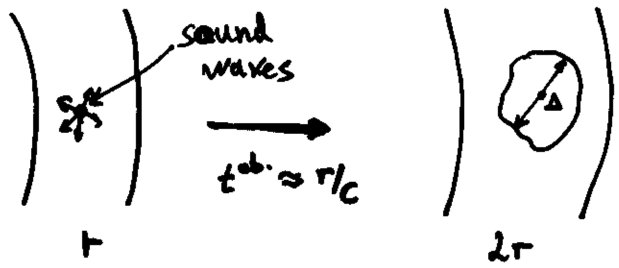
  Kinetic energy dissipation $\to$ Radiation.

(5) Dissipation Of Kinetic Energy

[Paczyński & Xu 94, ApJ 427, 708

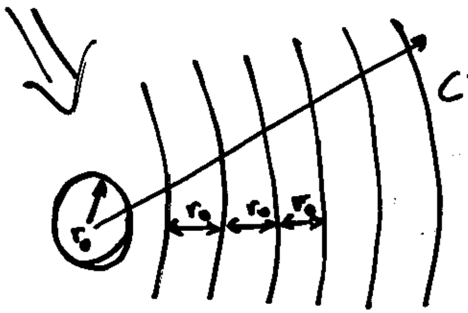
Mészáros & Rees 94, MNRAS 269, 41P]

- Causality :



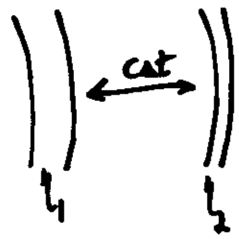
$t^{fb} = t^{ob}/\gamma$, $\Delta^{fb} = c_s \cdot t^{fb} \approx c\, t^{fb} \approx r/\gamma$

$\Delta_r^{ob.} = \Delta^{fb}/\gamma \approx r/\gamma^2 = \frac{r_0}{r} \cdot r_0 < r_0$



Causally disconnected Shells , $\Delta \approx r_0$

- Source variability :



If $\eta_1 > \eta_2 \Rightarrow \Gamma_1 > \Gamma_2 \Rightarrow$ Collision at

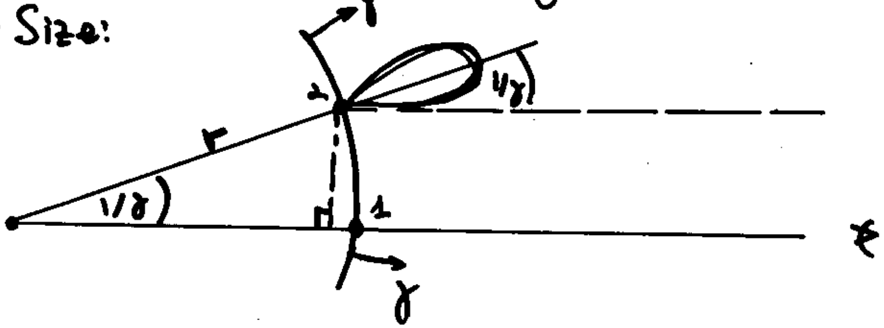
$$r = \frac{c\Delta t}{\Delta v} \cdot c \ , \quad \Delta v \cong c\left(\frac{1}{2\Gamma_2^2} - \frac{1}{2\Gamma_1^2}\right) \approx \frac{1}{2\Gamma_2^2} c$$

$$\Rightarrow \quad r_{coll.} \approx 2\Gamma_2^2 c \Delta t$$

$$r_{coll.} \approx \eta^2 r_0 \gg \eta r_0 \gg r_0$$

(2') Optical Depth: Expanding Source

• Size:



$$c\Delta t_{12}^{ob} = r\left[1-\cos\left(\frac{1}{\gamma}\right)\right] = \frac{r}{2\gamma^2} = \frac{r_{coll}}{2\gamma^2} = c\Delta t_{source}$$

$$\Rightarrow \quad r = 2\gamma^2 c\Delta t^{ob}$$

• Width:

$$t_2^{ob} \approx \frac{r}{c} \;\to\; t_2^{fb.} \approx \frac{r}{\gamma c} \;\to\; \delta\Delta^{fb} \approx \frac{r}{\gamma}$$

$$\to \delta\Delta^{ob.} \approx r/\gamma^2 \approx c\Delta t^{ob}$$

$$\Rightarrow \quad \Delta^{ob} \approx c\Delta t^{ob}, \quad \Delta^{fb.} \approx \gamma c\Delta t^{ob.}$$

Optical depth for photon at $\mathcal{E}_1^{ob.}$:

$$\tau_{\gamma\gamma} = \gamma c\Delta t \cdot \frac{3}{16}\sigma_T \cdot n_\gamma(>\mathcal{E}_{thr.})$$

$$\left(\frac{1}{\gamma}\mathcal{E}^{ob.}\right)\cdot \mathcal{E}_{thr.}\,(1-\cos\theta) \geq 2(m_ec^2)^2$$

$$\Rightarrow \quad \mathcal{E}_{th.} \approx 2\gamma\frac{(m_ec^2)^2}{\mathcal{E}^{ob.}}$$

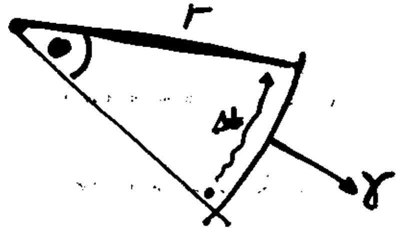
$$L = 4\pi r^2 c\,\gamma n_\gamma\cdot(m_ec^2)$$

$$n_\gamma(>\mathcal{E}_{thr.}) = n_\gamma\cdot\left(\mathcal{E}_{thr.}\Big/\frac{m_ec^2}{\gamma}\right)^{-1}$$

$$\tau_{\gamma\gamma} = \frac{3}{4}\,\frac{1}{128\pi}\,\frac{\sigma_T L\,\mathcal{E}^{ob.}}{(m_ec^2)^2\gamma^6\Delta t}$$

$$\tau_{\gamma\gamma}<1 \quad \Leftrightarrow \quad \gamma \geq 250\left[\frac{L_{52}}{\Delta t_{10ms}}\,\frac{\mathcal{E}^{ob.}}{100\,MeV}\right]^{1/6}$$

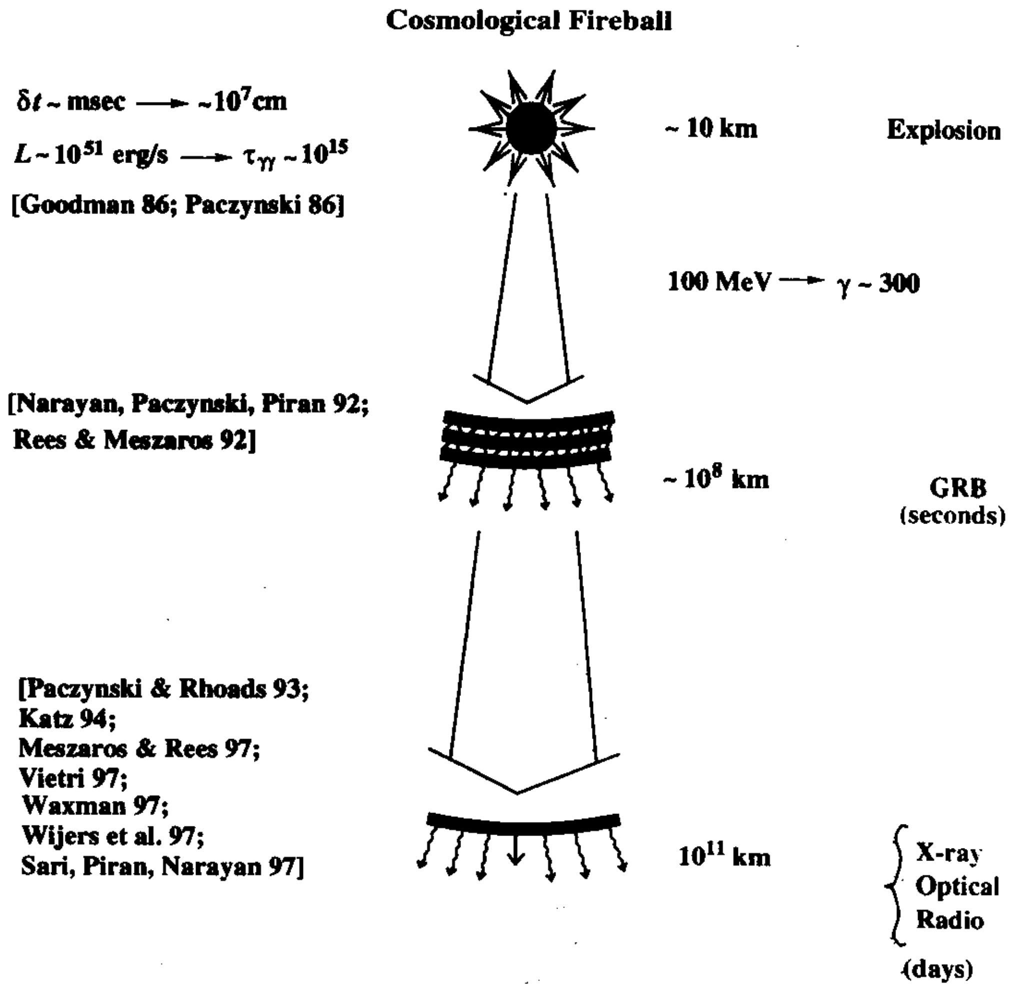
(6) Jet / Sphere ?



$$\Delta t^{fb} \simeq \frac{\theta r}{c} \Rightarrow \Delta t^{ob} \simeq (\gamma\theta)\frac{r}{c}$$

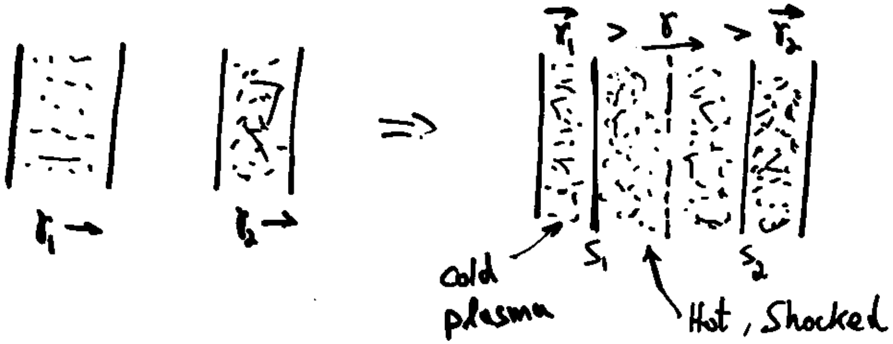
$\Rightarrow$ For $\theta > 1/\gamma$ the sideways crossing time is $> r/c$

$\Rightarrow$ For $\theta > 1/\gamma$ A Jet evolves like a conical section of a full sphere.



III. Radiation

(1) The Shocks



- Shocks are "collisionless": particle collisions are too rare; Coupling by Plasma Instabilities.

- $\gamma_1 / \gamma_2 \sim$ few $\Rightarrow \quad T_p \approx m_p c^2$

- Non-thermal particle distribution:

$$\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-p} \quad , \quad \frac{dN_p}{d\gamma_p} \propto \gamma_p^{-p} \quad ; \quad p \approx 2$$

for $\quad \gamma_e > \gamma_{e,min} \quad , \quad \gamma_p > \gamma_{p,min}$

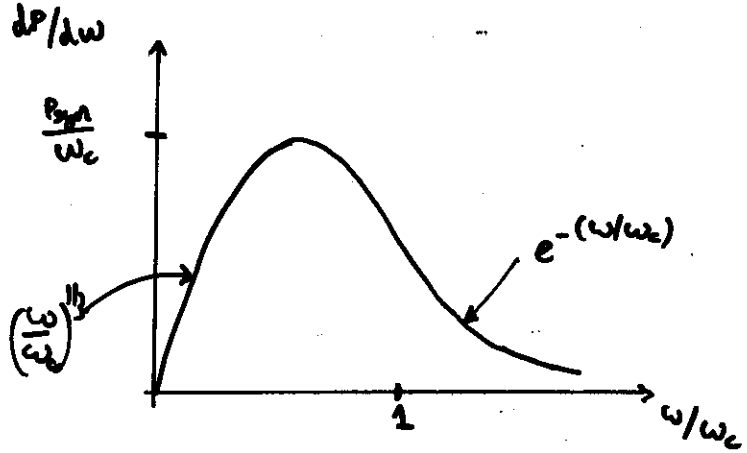
(2) Synchrotron Emission:

[Rybicki & Lightman, Radiative Processes in Astrophysics]

- e^- acceleration in B field:

$$P_{syn.} = \frac{4}{3} \sigma_T c \beta_e^2 \gamma_e^2 \left(\frac{B^2}{8\pi} \right)$$

$$\omega_c = \gamma_e^2 \frac{eB}{m_e c}$$



- $\tau_{syn} \equiv \frac{\gamma_e m_e c^2}{P_{syn.}} \propto \gamma_e^{-1}$

• GRB:

$$L_w = 4\pi r^2 \cdot c \cdot \gamma^2 U$$

$$U_B = \xi_B U$$

$$U_e = \xi_e U \rightarrow \gamma_e \approx \xi_e \frac{m_p}{m_e}$$

$U_e \rightarrow \gamma$-rays : $L_\gamma \approx \xi_e L_w$

$r \approx \gamma^2 c \Delta t$

$$\Rightarrow \gamma \cdot \hbar\omega_c \approx 1\, \xi_B^{1/2} \xi_e^{3/2} \frac{L_{\gamma,52}^{1/2}}{\gamma_{2.5}^2 \Delta t_{-2}} \text{ MeV}$$

! Theory for determining ξ_e, ξ_B – not available at present;

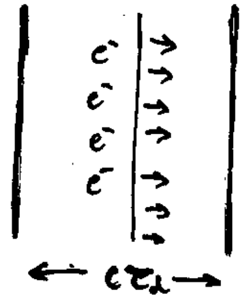
$\xi_e \sim \xi_B \sim 1$ Required.

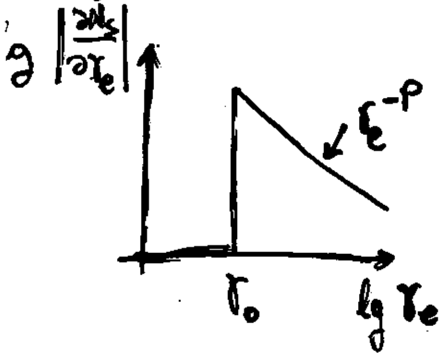
(3) e^- Energy distribution:

• $$\dot N_e(>\gamma_e) = \dot N_s(>\gamma_e) - \dot\gamma_e \frac{\partial N_e(>\gamma_e)}{\partial \gamma_e}$$

shock acceleration

syn. cooling



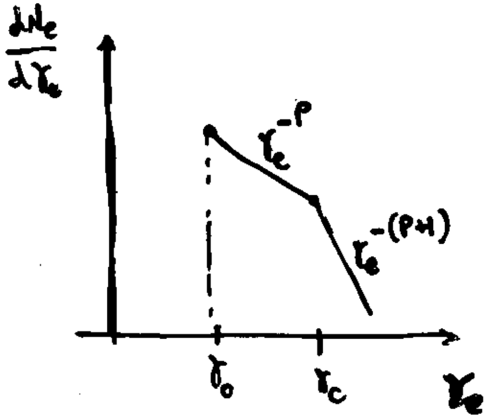


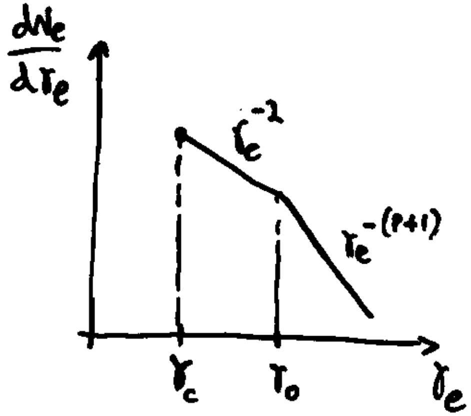
$$\tau_{syn.} = \tau_0 \left(\frac{\gamma_e}{\gamma_0}\right)^{-1}$$

$$\dot\gamma_e = -\frac{1}{\gamma_0 \tau_0} \gamma_e^2$$

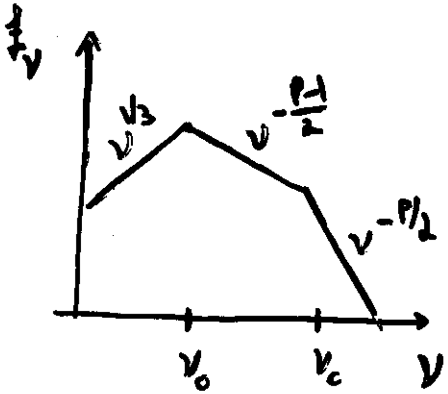
• $\tau_{syn}(\gamma_c) = \tau_d$: $\gamma_c = \frac{\tau_0}{\tau_d}\gamma_0$

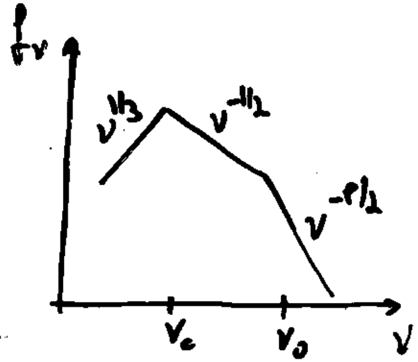
$$t = \tau_d : \begin{cases} \gamma_e \ll \gamma_c \rightarrow N_e(>\gamma_e) = \tau_d \dot N_s(>\gamma_e) \\ \gamma_e \gg \gamma_c \rightarrow \dot\gamma_e \frac{\partial N_e(>\gamma_e)}{\partial \gamma_e} = \dot N_s(>\gamma_e) \end{cases}$$





$$\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-\alpha} \Rightarrow \text{Syn.}: \quad f_\nu \propto \nu^{-\frac{\alpha-1}{2}} \qquad \left[f_\nu = \frac{df}{d\nu}\right]$$





- GRB:

$$\tau_{syn} \ll \tau_d \sim \gamma \Delta t$$

for any $\gamma_e > 1$

$\Rightarrow$ High-energy $f_\nu \propto \nu^{-1} \Leftrightarrow \frac{dN_e}{d\gamma_e} \propto \gamma_e^{-2}$

Consistent with shock acceleration.

! Low-energy:

Several examples with

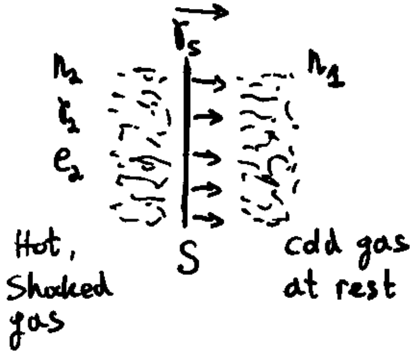
$f_\nu \propto \nu^\alpha$, $\alpha > 1/3 > -1/2$

IV. Interaction with Ambient Gas

OR: "After Glow"

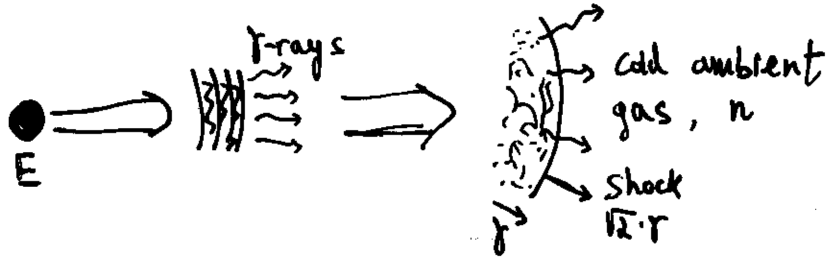
(1) Hydrodynamics:

[Blandford & McKee 76, Phys. Fluids 19, 1130]



$$\begin{cases} n_2 = 4\gamma_2 n_1 \\ e_2 = 4\gamma_2^2 n_1 m_p c^2 \\ \gamma_2 = \frac{1}{\sqrt{2}}\gamma_s \end{cases}$$

"Taub Adiabat"



$$E \approx \frac{4\pi}{3} r^3 n \cdot \gamma^2 m_p c^2$$

$$\Rightarrow \quad \gamma \approx \left(\frac{3}{4\pi}\frac{E}{n m_p c^2}\right)^{1/2} r^{-3/2}$$

(2) After Glow:

[Gruzinov & Waxman 99, ApJ 511, 852]
Sari, Piran & Narayan 98, ApJ 497, 47]

(-) $t^{ob} \approx \frac{r}{2\gamma^2 c} \propto r^4 \quad \rightarrow \quad \gamma \propto t^{-3/8}$

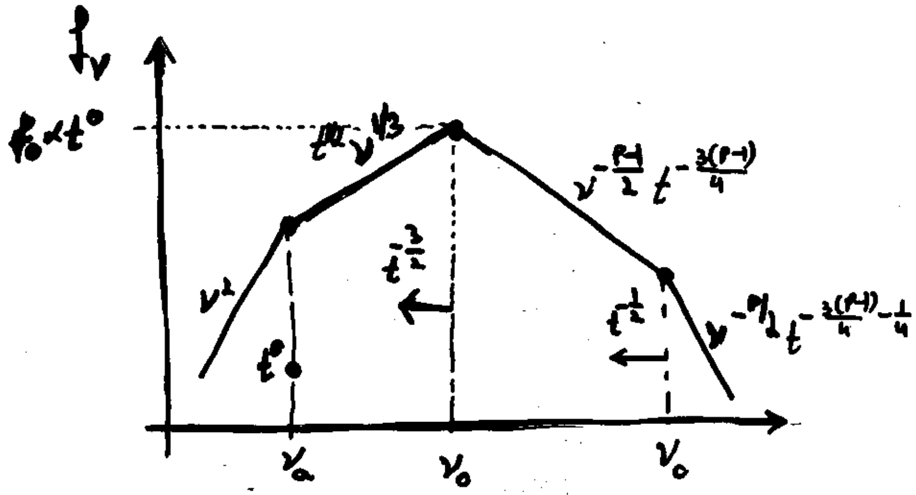
(-) $\gamma_{e,0} \approx \xi_e \frac{m_p}{m_e}\gamma_{p0} \approx \xi_e \frac{m_p}{m_e}\gamma \Rightarrow \gamma_{e,0} \propto \gamma$

$\frac{B^2}{8\pi} = \xi_B e_2 \propto \gamma^2 \Rightarrow \quad \Rightarrow B \propto \gamma$

$\Rightarrow \quad \nu_0 = \gamma \cdot \gamma_{e,0}^2 \frac{eB}{m_e c} \frac{1}{2\pi} \propto \gamma^4 \propto t^{-3/2}$

(-) $N_e \propto r^3 \propto t^{3/4}$

$\Rightarrow \quad f_\nu(\nu_0) = \gamma \cdot N_e \cdot \left(\frac{P_{syn}}{\omega_c}\right) \propto \gamma N_e \cdot B \propto t^0$



$$\nu_m = 10^{13}\left(\frac{\xi_e}{0.2}\right)^2\left(\frac{\xi_B}{0.1}\right)^{1/2}\sqrt{\frac{1+z}{2}}\,E_{52}^{1/2}\,t_d^{-3/2}\ \mathrm{Hz}$$

$$f_m = 4\,h_{75}^2\left(\frac{\sqrt{2}-1}{\sqrt{1+z}-1}\right)^2\left(\frac{\xi_B}{0.1}\right)^{1/2}E_{52}\,n_0^{1/2}\ \mathrm{mJy}$$

$$\nu_a = 2\left(\frac{1+z}{2}\right)^{-1}\left(\frac{\xi_e}{0.2}\right)^{-1}\left(\frac{\xi_B}{0.1}\right)^{1/5}E_{52}^{1/5}\,n_0^{3/5}\ \mathrm{GHz}$$

$$\nu_c = 10^{14}\left(\frac{\xi_B}{0.1}\right)^{-3/2}n_0^{-1}\,E_{52}^{-1/2}\left(\frac{1+z}{2}\right)^{-1/2}t_d^{-1/2}\ \mathrm{Hz}$$

$\Omega=1,\ \Lambda=0,\quad H_0 = 75\,h_{75}\ \mathrm{km/s\cdot Mpc}$

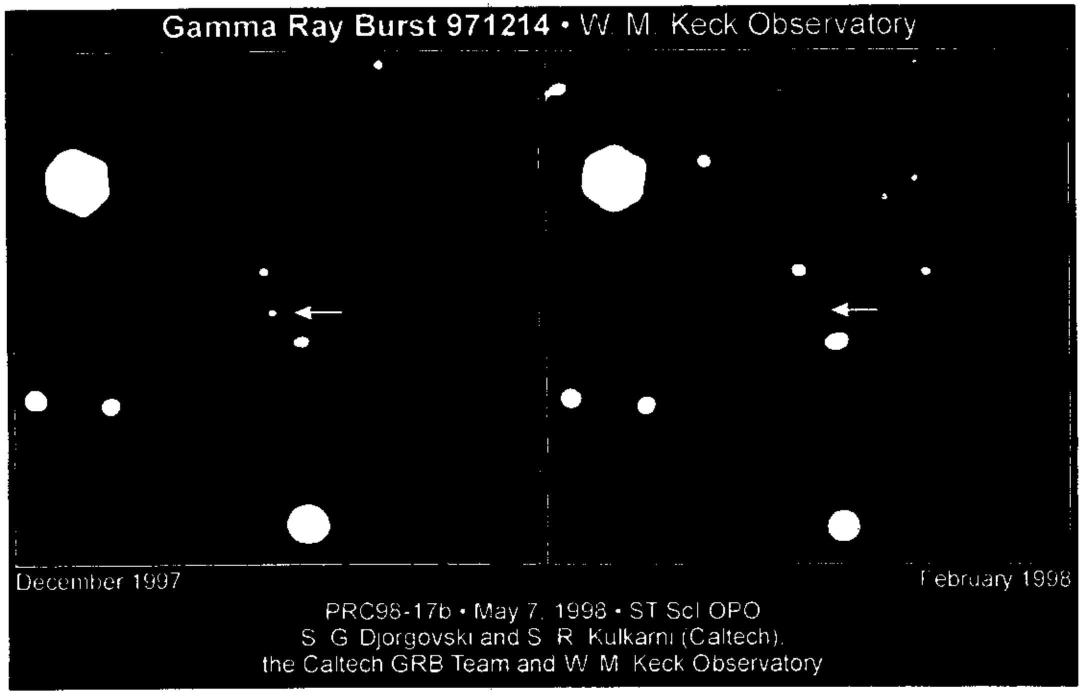
Model Parameters: E, n, ξ_e, ξ_B

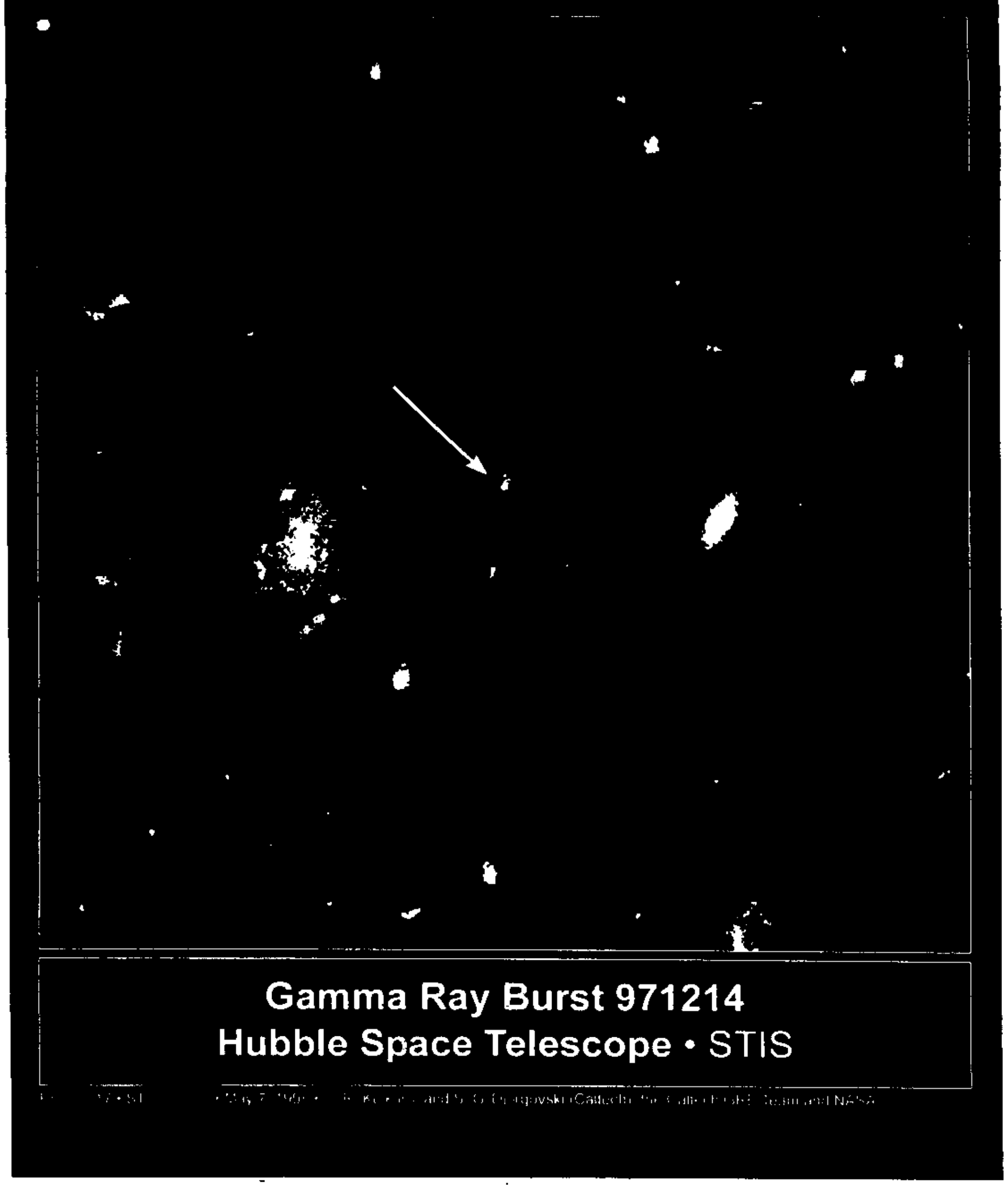
Observables : ν_m, ν_a, ν_c, f_m

$\mathrm{mJy} = 10^{-26}\ \mathrm{erg/cm^2\cdot s\cdot Hz}$

After Glows: What we have learned from Observations

[Review: Kulkarni et al. 2000 astro-ph/0002168]


Gamma Ray Burst 971214 • W. M. Keck Observatory
December 1997
February 1998
PRC98-17b • May 7, 1998 • ST ScI OPO
S. G. Djorgovski and S. R. Kulkarni (Caltech),
the Caltech GRB Team and W. M. Keck Observatory


Gamma Ray Burst 971214
Hubble Space Telescope • STIS

Redshift Distribution

TABLE 1. Basic Properties of Selected GRBs

GRB	α(J2000) (h m s)	δ(J2000) (° ′ ″)	R_{host} (mag)	$S \times 10^{-6}$ (erg cm^{-2})	z	References[a]
970228	05 01 47	+11 46.9	25.2[b]	1.7	0.695	Djorgovski et al. GCN 289
970508	06 53 49	+79 16.3	25.7	3.1	0.835	[60,2]
970828	18 08 32	+59 18 52	TBD	74	0.957	[12]
971214	11 56 26	+65 12.0	25.6	11	3.418	[46]
980326	08 36 34	−18 51.4	$\gtrsim$ 27.3	1	…	
980329	07 02 38	+38 50.7	25.4	50	…	
980519	21 22 21	+77 15.7	26.2	25	…	
980613	10 17 58	+71 27.4	24.5	1.7	1.096	Djorgovski et al. GCN 189
980703	23 59 07	+08 35.1	22.6	37	0.966	[11]
981226	23 29 37	−23 55 54	$\gtrsim$ 22	N.A.	…	
990123	15 25 31	+44 46 00	24.4	265	1.600	[46]
990510	13 38 07	−80 29 49	$\gtrsim$ 28	23	1.619	Vreeswijk et al. GCN 324
990712	22 31 53	−73 24 29	21.78	N.A.	0.430	Galama et al. GCN 388
991208	16 33 54	+46 27 21	$\gtrsim$ 25	100	0.706	Dodonov et al. GCN 475
991216	05 09 31	+11 17 07	24.5	256	1.020	Vreeswijk et al. GCN 496

[a] References to redshift determination.
[b] V-band magnitude from HST. All others are R magnitude in the Johnson system.

Most: $0.5 < z < 1.5$

"Record": $z = 3.4$

$$R_{GRB} = \int_{z_1}^{z_2} dz \, \frac{c\,dt}{dz} \cdot 4\pi R(z)^2 \, r(z)^2 \, \frac{1}{1+z} \, \dot{n}_0 \, (1+z)^{3+\alpha} \equiv V(z_1,z_2)\, \dot{n}_0$$

$\Omega = 0.3,\ \Lambda = 0.7 \quad \Rightarrow \quad \dot{n}_{GRB}(z=1) \simeq 4 \cdot 10^{-9}\ \mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}\ h_{75}^{3}$

Scintillation

Scattering by electron density fluctuations in the local inter-stellar gas

$\Rightarrow$ Strong flux variations provided:

1. Multiple images produced:

   $$\nu < \nu_o(d_{\mathrm{sc.}}, \mathrm{SM}) \simeq 11\ \mathrm{GHz}$$

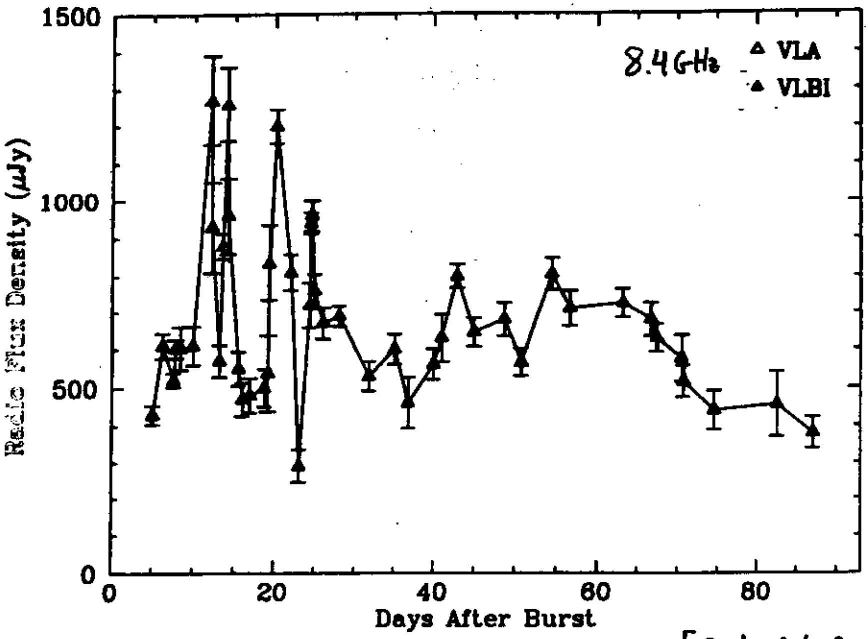
2. Apparent source size:

   $$h < h_o(d_{\mathrm{sc.}}, \mathrm{SM}) \simeq 10^{17}\ \mathrm{cm}$$

[Goodman 97]

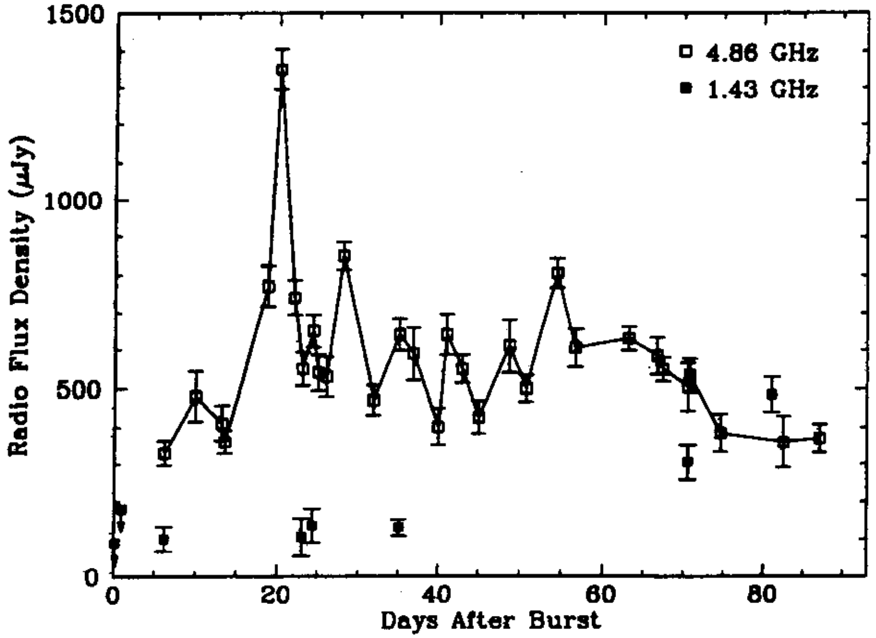
Fireball: $h = 8 \times 10^{16} (E_{52}/n_1)^{1/8} t_{\mathrm{week}}^{5/8}$ cm

[Waxman 97]



Wax--

[Frail et al. 97, Nat. 389, 261

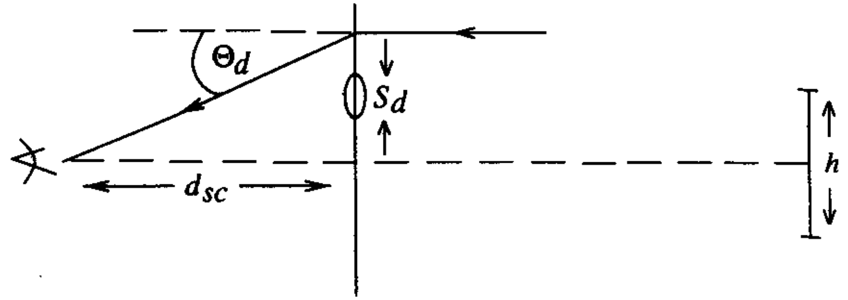


Scintillation

Scattering by ISM n_e fluctuations:

$$|\delta n\,(\underline{K})|^2 = C_N^2 K^{-11/3} \;\Rightarrow\; S_d = \tfrac{2\pi}{K_d} \cong 3{\cdot}10^{10}\left(\tfrac{\nu}{10\ \mathrm{GHz}}\right)^{6/5} SM^{-3/5}\ \mathrm{cm}$$

$$SM \equiv \int dx \cdot C_N^2/10^{-3.5}\ \mathrm{kpc}\cdot m^{-20/3}$$



Strong Modulation:

(1) Multiple images: $\Theta_d \cdot d_{sc} > S_d$

$$\nu < 11\left(\tfrac{d_{sc}}{1\ \mathrm{kpc}}\right)^{6/17} SM^{5/17}\ \mathrm{GHz}$$

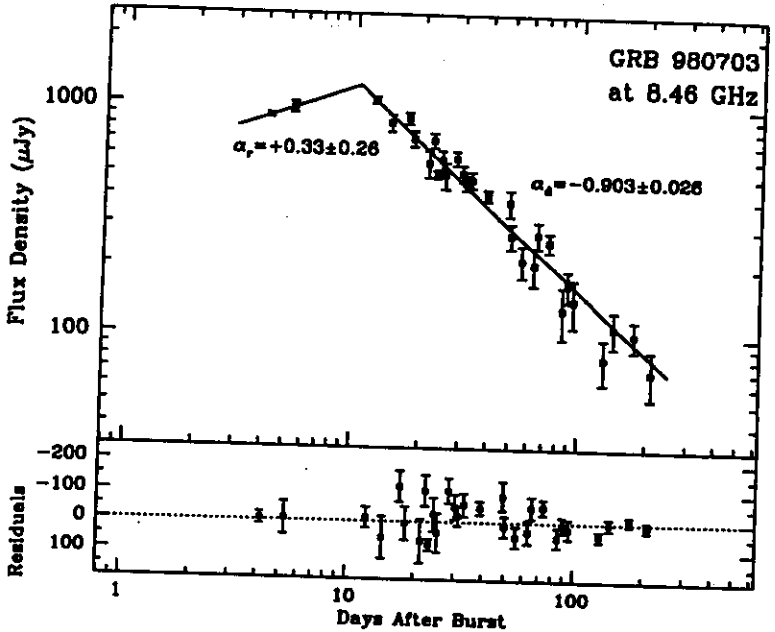
(2) $\frac{h}{d_A} < \frac{S_d}{d_{sc}}$: $\quad h < 1.1 \cdot 10^{17}\left(\frac{dsc}{1\ \mathrm{kpc}}\right)^{-11/17} H_{75}^{-1} SM^{-3/17}\ \mathrm{cm}$

$$h = 8 \cdot 10^{16} t_{\mathrm{week}}^{5/8}\ \mathrm{cm}\left(\tfrac{E_{52}}{n_1}\right)^{1/8}$$

[Goodman 97]

GRB 980703

Radio Light Curve & Spectrum



GRB 970508

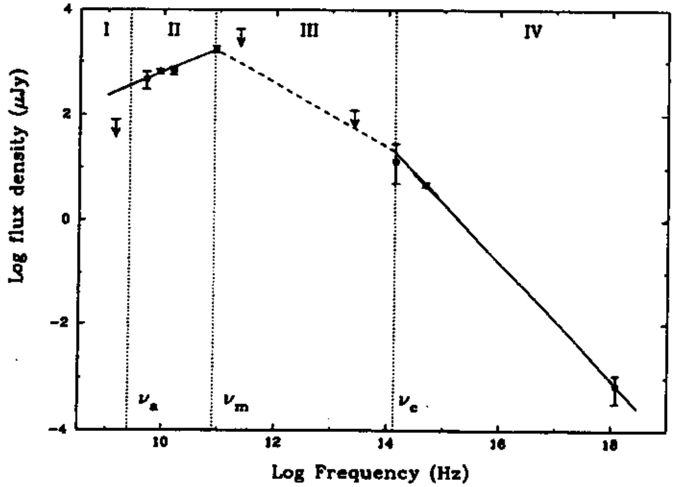
$E = 10^{52}$ erg [Isotropic]

$n = 1\ \mathrm{cm}^{-3}$

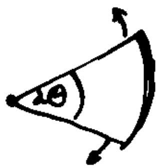
$\xi_e \simeq \xi_B \simeq 0.1$

$t = 12$d spectrum

radio ↓ opt. ↓ X-ray ↓



(3) Jets



• Sideways expansion once

$$\theta < \gamma^{-1} = 0.1 \left(\frac{E_{53}}{n_0}\right)^{-1/8} t_d^{3/8}$$

• $t_{s.w.e.} \approx r_{s.w.e.}/c$

⇒ $r \sim$ const. during s.w.e.

(-) $t^{ob.} = r/\gamma^2 \Rightarrow \gamma \propto t^{-1/2}$

(-) $\nu_m \propto \gamma \cdot \gamma_e^2 \cdot B \propto \gamma^4 \propto t^{-2}$; $\nu_c \propto t^0$

(-) $f_m \propto t^{-1}$

$\nu_c > \nu > \nu_m$: $f_\nu \propto t^{-p} \nu^{-\frac{p-1}{2}}$

[Spherical: $f_\nu \propto t^{-\frac{3(p-1)}{4}} \nu^{-\frac{p-1}{2}}$]

Stanek et al. 99
ApJ 522, L39

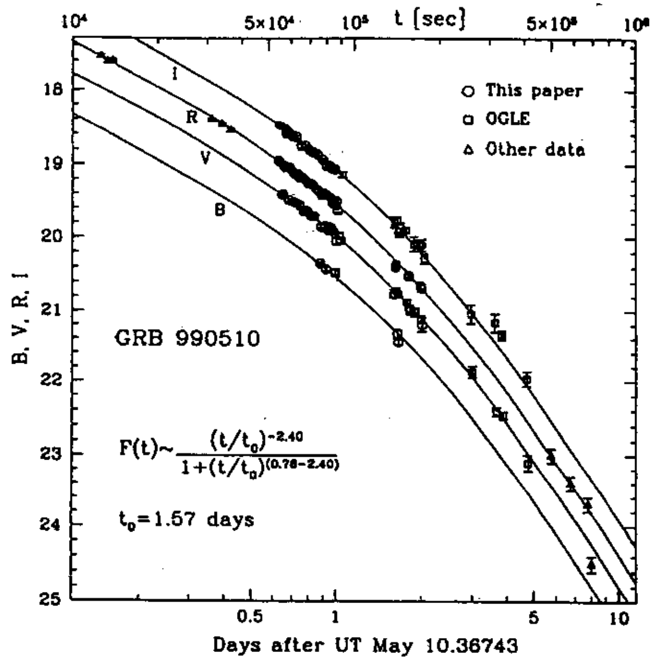


FIG. 2.—*BVRI* light curves of GRB 990510. Our data is shown with circles and OGLE data with squares. Other data used to constrain the fits is shown with triangles (for references see text). Also shown is the simple analytical fit discussed in the text.

GRB 970508 : Fireball Calorimetry

Wax

[Frail et al., astroph/9910319]

- Deviation from model @ $t > 25d$ suggest:

  $\theta \sim 0.5$ Jet $\Rightarrow$ $E = \frac{\theta^2}{4} \cdot 10^{52} erg \simeq 10^{51} erg$

  Sub-relativistic @ $t > 100d$

- Confirmed by $t > 100d$ radio observations.

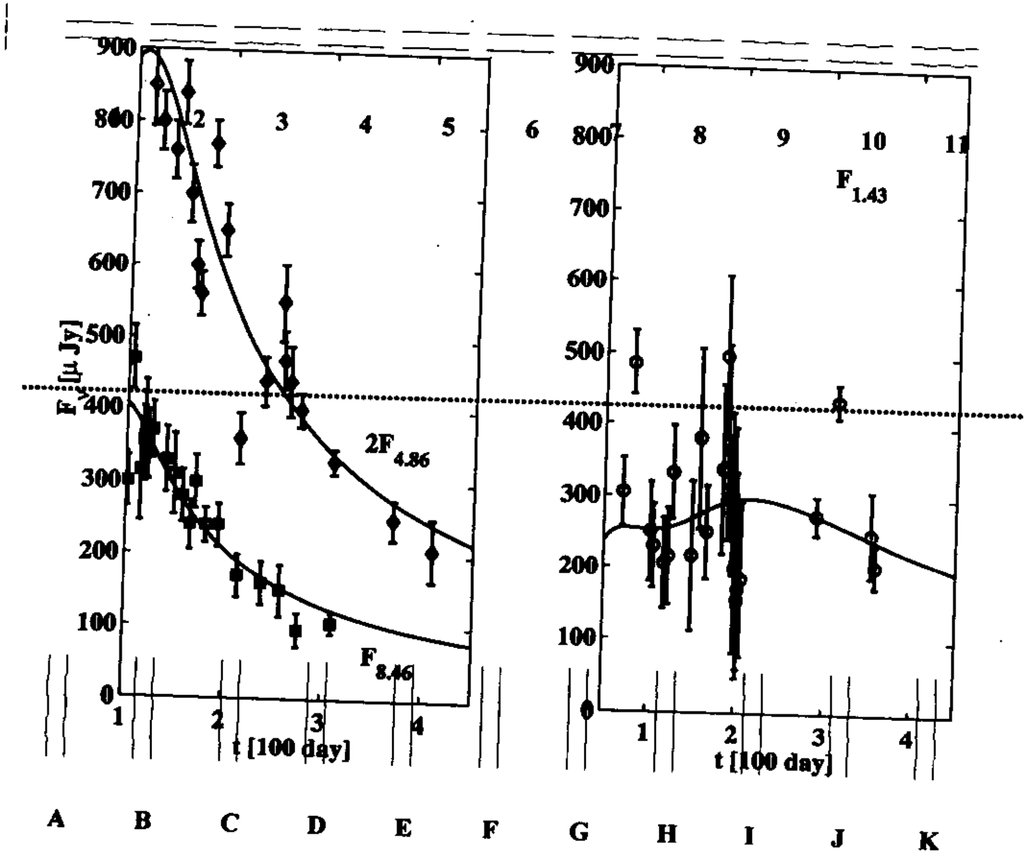
  Sub-relativistic model:

  $E_{Tot.} \simeq 5 \cdot 10^{50} erg$

  $\Delta\Omega / 4\pi \approx 5 \cdot 10^{50} / 10^{52} \approx 0.1$

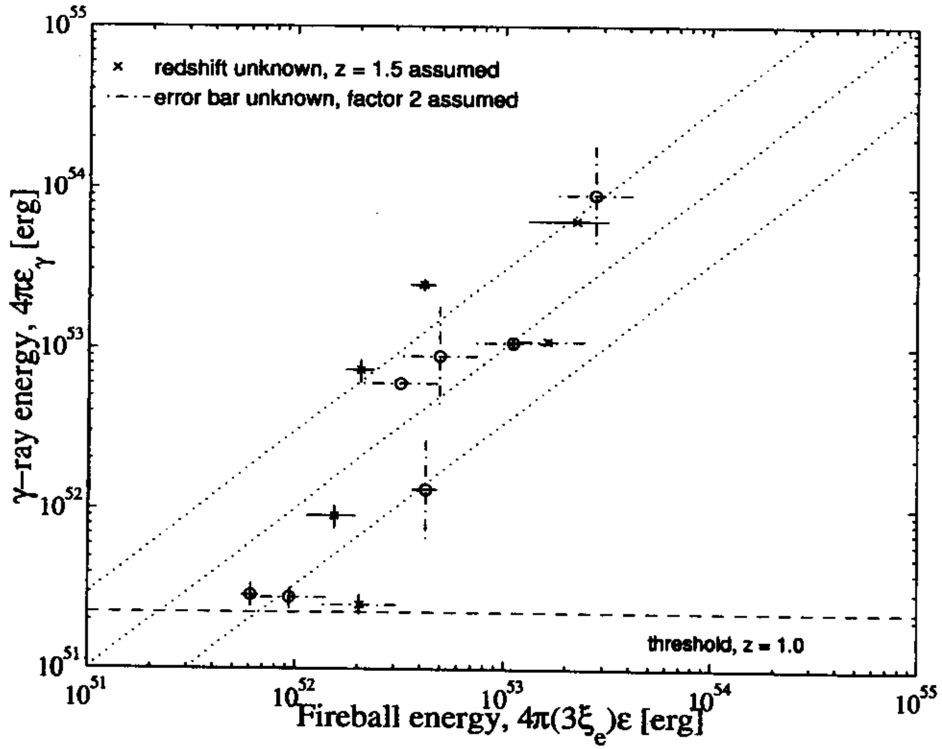
  $n = 1\ cm^{-3}$

  $\xi_e \sim \xi_B \sim 0.5$



[Freedman & Waxman 99

Wax-

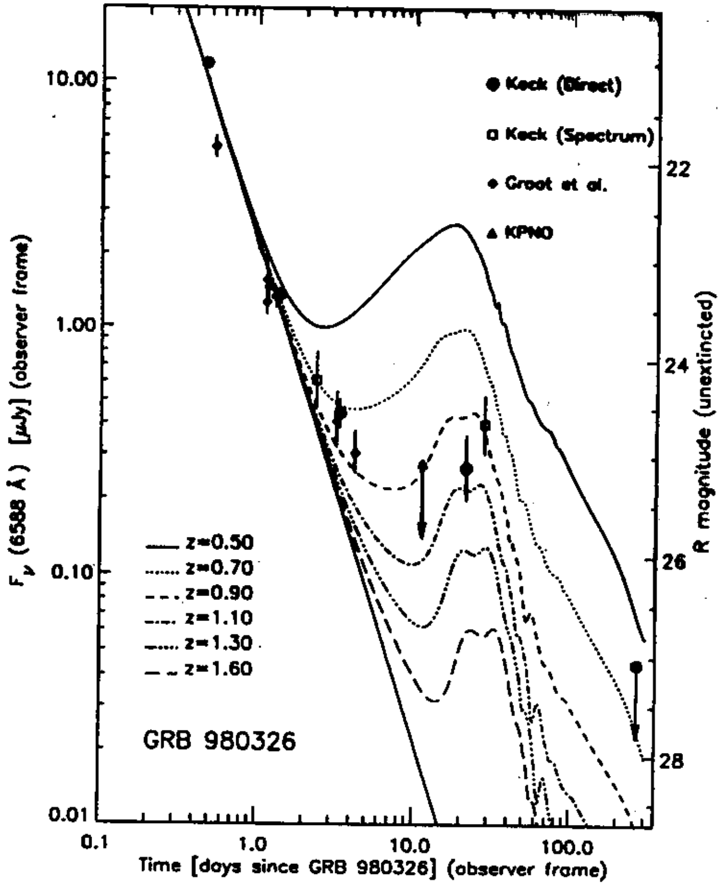


(4) Association with Super-Novae

- GRB980425 $\leftrightarrow$ Temporal and angular coincidence with SN1998bw

  [Chance coincidence : $\sim 10^{-4}$]

- GRB980326 : "Strange" light-curve



IV Summary: What we have learned

- GRBs $\leftrightarrow$ Cosmological, Relativistic Fireballs
- E_γ (Isotropic) $= 10^{52} - 10^{54}$ erg

  $$E_\gamma = 10^{52} - 10^{54} \frac{\Delta\Omega}{4\pi} \text{ erg}$$
- Rate $(z=1) \simeq 4 \cdot 10^{-9} \left(\frac{4\pi}{\Delta\Omega}\right) / \text{Mpc}^3 \text{ yr}$
- GRB970508:

  $E \simeq E_\gamma = 10^{52} \frac{\Delta\Omega}{4\pi}$ erg

  $E = 10^{51}$ erg $\rightarrow$ $\Delta\Omega / 4\pi \simeq 0.1$

  $n \simeq 1 \text{ cm}^{-3}$, $\xi_e \approx \xi_B \sim 0.5$
- Evidence for Jets, $\theta \sim 0.1$
- Association with SNe ?

IV Summary: Open Questions

- Underlying Source:

  Neutron Star Mergers [Paczyński 86, Goodman 86]

  Massive Star Collapse [MacFadyen & Woosley 99 ApJ 524, 262]

- Shock wave processes: $\{\xi_e, \xi_B\}$

- $T \sim 0.2$ GRBs : No AfterGlow [No BeppoSAX trigger]

New GRB Location Satellites:

HETE II (7/00)

SWIFT