Thermal Emission in Gamma-Ray Burst Afterglows

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Supernovae and Gamma-Ray Bursts Workshop
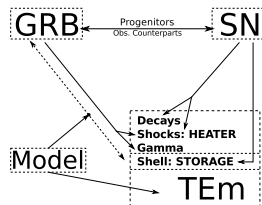Kyoto, November 5th, 2013

SAI MSU

Outline

- Brief introduction
- The model and modeling
- Results of simulations
- Test against observations

Why Thermal Emission in Afterglows?

General considerations: a lot of matter (previously ejected by the massive progenitor star) + a lot of energy ($10^{51} - 10^{53}$ erg) $\Rightarrow$ **Thermal Emission** (TE). Analogy with supernovae.
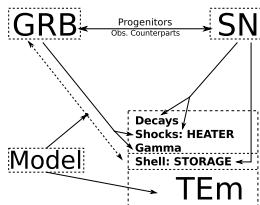

Observational evidence:

- well known SN-bumps (the most obvious signature of TE in GRBs, *Woosley & Bloom 2006, Cano et al. 2011*)

- more earlier optical light curve irregularities (deviations from a power law fading) sometimes observed in afterglows. At least some of them may have thermal nature.

'Thermal trend' in prompt emission studies

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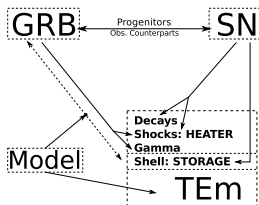

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Picture of a Model

A massive star $\rightarrow$ Pulsations or instabilities $\rightarrow$ 1-st ejection $\rightarrow$ 2-nd ejection, ejected masses collide and form structures (e.g. dense shells, *Ofek et.al, 2013*). $\rightarrow$ ... $\rightarrow$ ⊛ GRB, the shell is illuminated by prompt emission and then the relativistic ejecta runs into it.
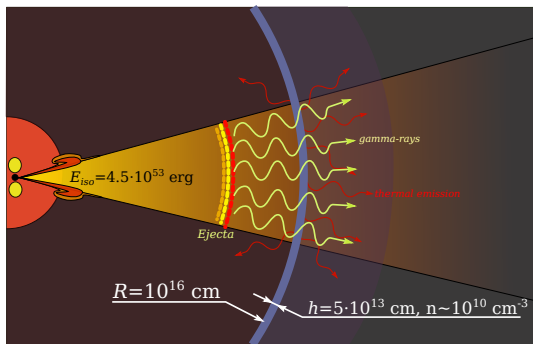
The shell gains energy and should radiate it.

Essentials ...

Modeling with the STELLA code

The STELLA code, originally developed for supernova light curve simulations, (*Blinnikov et al., 1998*)

- multigroup time dependent radiation hydrodynamics
- Non-relativistic ($O(v/c)$), spherically symmetric,
- Lagrangean coordinates, staggered mesh.
- Full implicit time-dependent predictor-corrector solver for stiff ODE systems, modified Gear method (*Brayton, Gustavson, Hatchel, 1972*), flexible dynamic step and error control.

Initial Model

- A continuous spherical shell discretized with 100 concentric mass coordinate layers. Particle density ($n \sim 10^{10}$ cm^{-3}) and extents ($r \sim 10^{16}$ cm, $\delta r/r = 0.005$).
- Resembles *Woosley, Blinnikov & Heger (2007)* pre-supernova shell. Abundances were taken from that paper.
- Also to ensure
  - significant intercepted energy;
  - no possibility for relativistic motions to appear
  - not great Thomson optical thickness ($\tau_T \sim 1$)
- Only radial structure is available, but is unimportant because of small relative thickness.
- Different models had been simulated, but such a 'wall' displays the most pronounced features.

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Basic Equations

Radiation:

$$\frac{\partial}{\partial t}\mathcal{J}_\nu = c(\eta_\nu - \chi_{ab}\mathcal{J}_\nu) - \frac{\partial(ur^2)}{r^2\partial r}\mathcal{J}_\nu - \frac{c}{r^2}\frac{\partial}{\partial r}(r^2\mathcal{H}_\nu)+$$

$$+ \left[1 - \frac{1}{\nu^3}\frac{\partial}{\partial \nu}(\nu^4...)\right]\left(\frac{u}{r}(3f_E - 1)\mathcal{J}_\nu - \frac{\partial(ur^2)}{r^2\partial r}f_E\mathcal{J}_\nu\right),$$

$$\frac{\partial}{\partial t}\mathcal{H}_\nu = -c(\chi_{ab} + \chi_{sc})\mathcal{H}_\nu - \frac{2}{r}\frac{\partial(ur)}{\partial r}\mathcal{H}_\nu-$$

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Hydrodynamics:

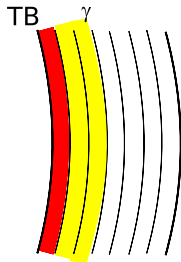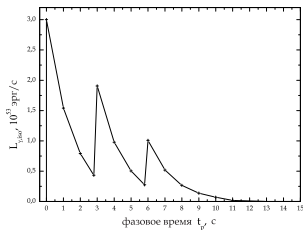$$\frac{\partial r}{\partial t} = u, \qquad \frac{\partial r}{\partial m} = \frac{1}{4\pi r^2\rho},$$

$$\frac{\partial u}{\partial t} = -4\pi r^2\frac{\partial(p+q_{vis})}{\partial m} - \frac{Gm}{r^2} + \frac{4\pi}{c}\int\limits_0^\infty \frac{\chi_{ab}+\chi_{sc}}{\rho}H_\nu d\nu + a_{mix}$$

$$\left(\frac{\partial e}{\partial T}\right)_\rho\frac{\partial T}{\partial t} = \epsilon + 4\pi\int\limits_0^\infty \frac{\chi_{ab}}{\rho}(J_\nu - B_\nu)d\nu - 4\pi\frac{\partial(ur^2)}{\partial m}(T\left(\frac{\partial p}{\partial T}\right)_\rho + q)$$

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New! Prompt Emission

- 3 FRED pulses $\times$ 1.5 s, total duration 15 s, isotropic $L_{peak} = 3 \cdot 10^{53}$ erg/s, broken power-law spectrum (1 keV–30 MeV, $\alpha = 0.9$, $\beta = 2.001$, $E_0 = 300$ keV), 100 energies. Assumed collimation $\theta_{jet} = 10°$

- Rapidly varying "external force":

$$\frac{\partial u}{\partial t} = \frac{4\pi}{c} \int_0^\infty \frac{\chi_{ab} + \chi_{sc}}{\rho} H_\gamma d\varepsilon_\gamma + ...,$$

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- χ_{ab}, χ_{sc} – photoionization, Compton scattering on b and f e^-

- One scattering approximation (accuracy $\sim 10\%$ in heating power), $J_\gamma \approx H_\gamma = \frac{L_\gamma e^{-\int \chi(r,t)ds}}{16\pi^2 r^2}$

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💥New! State of Matter

- Time dependent ionization kinetics $\frac{\partial \mathbf{n}_{zi}}{\partial t}|_\rho = \mathsf{R}(n_e)\mathbf{n}_{zi}$,
  15 elements $\Rightarrow \approx 200$ ion species $\to \mathbf{n}_{zi}$, n_e, p, ∂p, e, ∂e, χ,
  ... within $ct_\gamma = 15$ light seconds behind the γ-ray front $\to$

- Smooth transition to the Boltzmann-Saha solution

- The transition time scale should satisfy $n_e t \sim 10^{12}$, i.e.
  $10 - 100$ s.

- One temperature fluid $\approx$ valid for $t > 10^{12}/n_e$, though lacking
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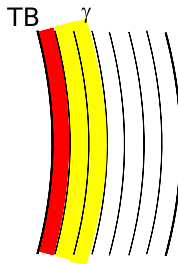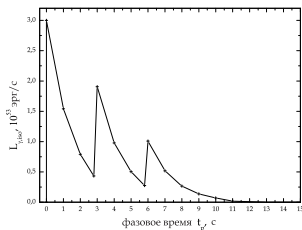
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New! The Ejecta

- Immediate deceleration $\frac{E_k}{c^2\Gamma} \leqslant M_{dec} < \frac{E_k}{c^2\Gamma^2} << M_{shell} \Rightarrow$ thermalization.

- Thermal energy $E_k = E_{iso,\gamma} = 4.5 \cdot 10^{53}$ erg is deposited into the innermost zone over $\delta R_z/c \approx 17$ s time scale. A 'Thermal Bomb' is triggered $\Delta t_{\gamma-ej} \sim \frac{R}{2c\Gamma^2} \approx 200$ s for $\Gamma = 30$.

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Thermal Emission

$$\frac{\partial \mathcal{J}_\nu}{\partial t} = c(\eta_\nu - \chi_{ab}\mathcal{J}_\nu) - \frac{\partial(ur^2)}{r^2\partial r}\mathcal{J}_\nu - \frac{c}{r^2}\frac{\partial}{\partial r}(r^2\mathcal{H}_\nu) +$$

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- Closure by Eddington factors: $f_E = \frac{\int_{-1}^{1}\mu^2 f d\mu}{\int_{-1}^{1} f d\mu}$ from simplified 2D-problem
  formal intergal solution.

- $O(v/c)$ aberration, Doppler shift, retardation;
  120 groups from 50000 Å to 100 keV

- Source $\eta_\nu = \chi_{ab}b_\nu$, χ_{ab} – f-f, b-f, lots of b-b + expansion.

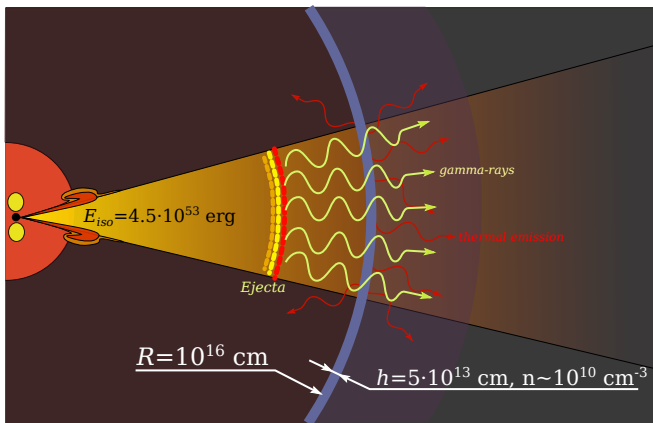- Boundary conditions: $\mathcal{H}_\nu = h_E\mathcal{J}_\nu$, outer: > 0; inner: < 0. $p_{out} = 0$.

Thermal Emission

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- <u>New!</u> Curvature delay: $L_{\nu,iso}(t_{obs}) = 8\pi^2 \int\limits_{\mu_{min}}^{1} \mu I_\nu(t'_{del}, \mu) R^2_{out}(t'_{del}) d\mu$,

  where $t'_{del} + \frac{R_{out}(t'_{del})}{c}(1 - \mu) = t_{obs}$
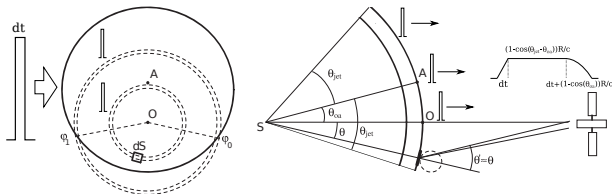
Model Overwiew

Model Overwiew

- A dense 'wall' of matter.
- 1D moment radiative transfer equation, Eddington factor closure
- Lagrangean radiation hydrodynamics implicit solver
- *New!* time-dependent ionization
- *New!* γ-ray affected microphysics and heating
- *New!* Additional heating by the ejecta
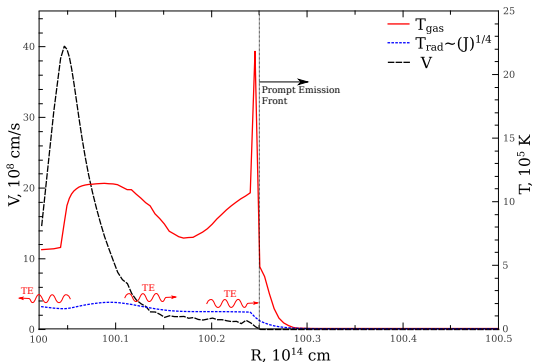- *New!* Curvature delay

Results: The Shell Hydrodynamics

▶ **A full ionization** ⇒ **PE and X-ray emission IS NOT ABSORBED** by the shell.

▶ **The radiation pressure dominates** and governs matter motions.

▶ **The ejecta** launches a strong shock, smeared by the TE, exhausting its energy through the inner boundary.

▶ **Coasting** velocity ≈3000 km/s. Free expansion.

Matter temperature, velocity and TE effective temperature $\sigma T_{rad}^4 = \pi \int J_\nu d\nu$ at the time, the PE has illuminated nearly half of the shell.

Thermal Emission properties

The high temperature peak produces a keV X-ray pulse following the PE front. Then comes a longer sub-keV soft X-ray tail (accounts for the most of the TE luminosity) and less energetic tails: UV, optical, IR – the softer the longer.
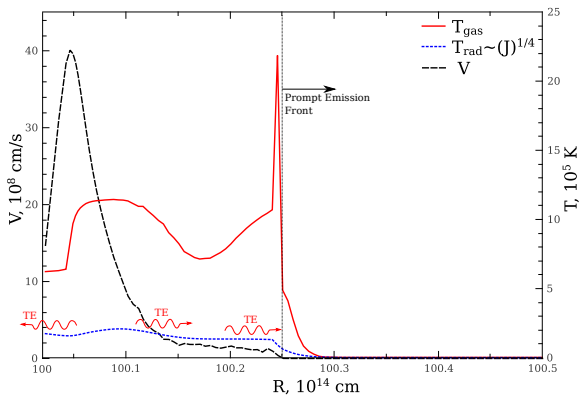
Thermal Emission properties

Shell curvature $\Rightarrow$ bright pulses turn into long flat suppressed bumps/plateaus with following characteristic times:

▶ **Rise time** $\approx$ radiation cooling time, e.g. $\sim$10-100 s in keV X-rays, $10^2 - 10^3$ s in soft X-rays.

▶ **Plateau duration** $\approx (1 - \cos(\theta_{jet}))R/c \approx 5000$ s for the "on axis" observer

▶ **Fade time**, a combination of the radiation cooling time and an off-axis angle delay.

$\Rightarrow$ **No plateau** for frequencies with radiation cooling times > 5000 s.

▶ **NB**. This picture may be complicated by light diffusion/reverberation in the shell.
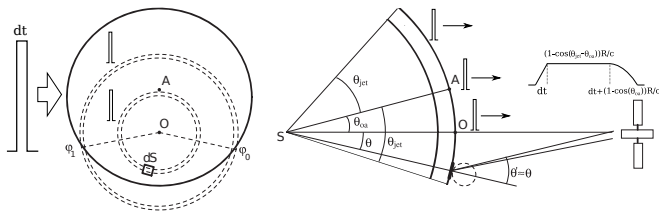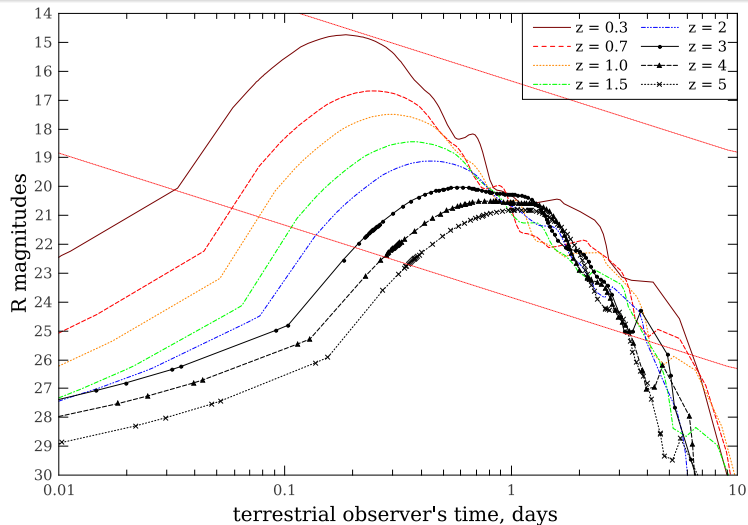
Luminosity light curves
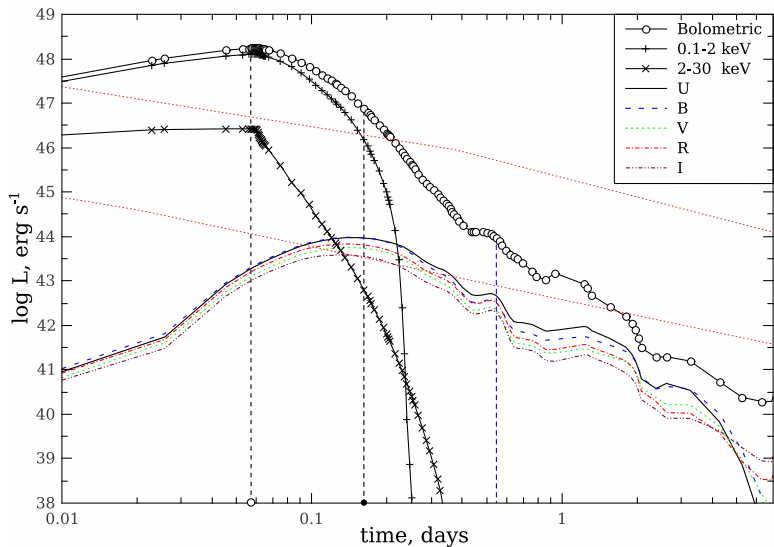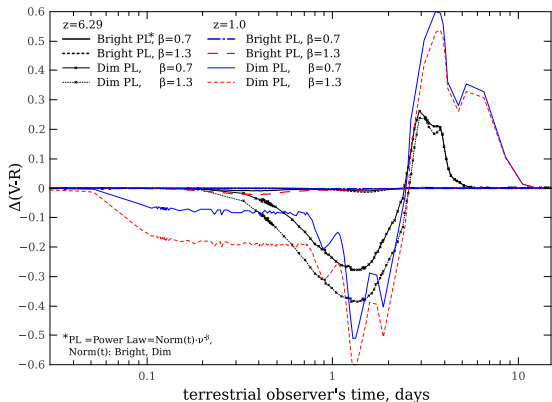
Luminosity spectral density
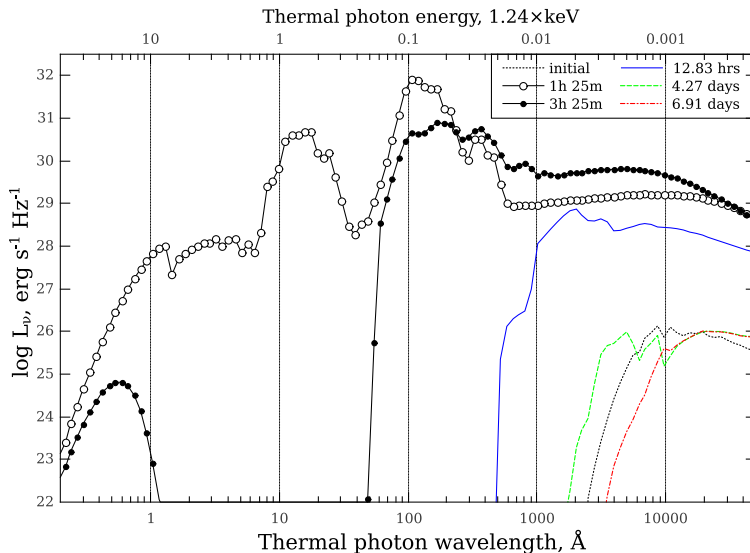
Stellar Magnitudes (Fluxes)

The most visible displays of TE in optics should be looked for in high-redshift objects' LCs

Effect on Color Evolution

$$\Delta(V - R) = (V - R)_{Sync+TE} - (V - R)_{Sync}$$

Color evolution from blue to red.

Valuable for the dimmest afterglows.

Negligible for the bright ones.

Red shift suppresses its visibility.

Observations: Optical Irregularities

▶ Irregularity ≡ a long term deviation from a power law fading
Possible candidates to be explained by TE.

GRB	z	$E^1_{\gamma,iso}$ 10^{53} erg	R^4_{bump} mag	t^5_{peak} days	t^6_{bump} days	β time-aver.
020124	3.198	1.6	18.36	0.47	≈ 7	0.56
021004	2.3351	0.1^2	16.2	0.08	0.5	0.67
			19.05	0.9	1.7	
030328	1.52	3.3	19.4	0.28	1.2	0.36
030429X	2.65	0.13^3	20.9	1.2	≈ 4	0.22
050904	6.29	6−32	20.5	0.32	≈ 7	...
Model	any	4.5	See	the	plots	

[1] converted into 1 keV – 10 MeV range; [2] 15-150 keV only, due to lack of observations; [3] the peak luminosity was $5 \cdot 10^{53}$ erg/s; [4] the magnitude at the deviation maximum; [5] the moment of the maximum; [6] the irregularity duration

▶ The afterglows with irregularities seem systematically 'bluer'
(their spectral slopes β are lower than typical $\beta = 0.7$).

Optical Irregularity Model
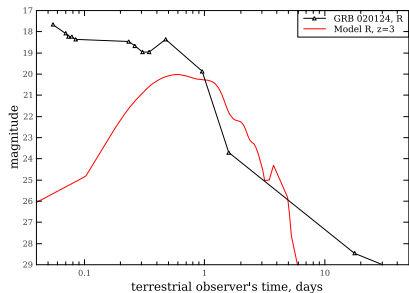
GRB 021004, z≈3   GRB 050904, z=6.29
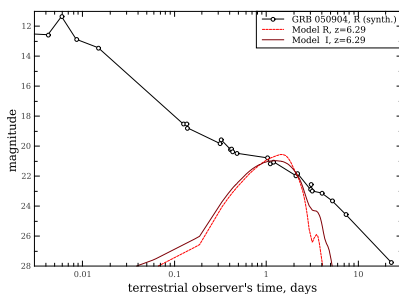
The relativistic ejecta encounters a strong density jump and radiates the **synchrotron emission** ⇒ **the smooth onset** (*Nakar & Granot, 2007*).
A characteristic moment of the onset is $(1+z)10\Delta t_{\gamma-sh} \sim (1+z)2000$ s, nearly that is observed. Heated matter then radiates its internal energy via **the TE** ⇒ **flat bump/plateau and fast fading**.

X-ray Irregularities

X-RAY PLATEAUS (or flat bumps)

▶ **X-ray light curves** GRB 050904 (also had an OI) and GRB 070110 (taken from *Troja et al., 2007*). 070110 had $F_\nu \approx 2\mu$Jy @1 keV, $\Leftrightarrow L_\nu \approx 5 \cdot 10^{29}$ erg s^{-1} Hz^{-1} @3.3 keV during the plateau, consistently with model spectra.

▶ **The smooth onset** – the same like in optics (?)

▶ But, an increasing HR $\frac{[1-10\,keV]}{[0.2-1\,keV]}$ from 1 to 1.5 was reported.

GRB 050904 and **GRB 070110**
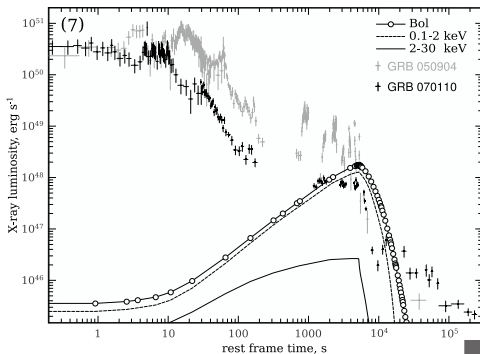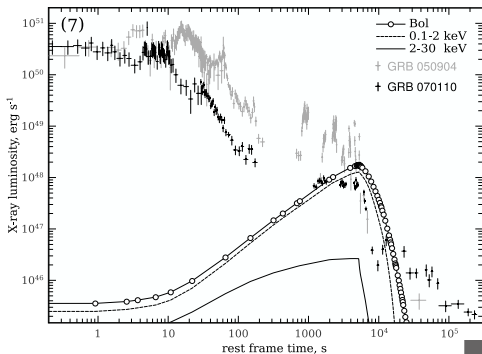
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GRB 050904 and **GRB 070110**

X-ray Irregularities

The hardness deficit may be overcome
taking into account:

- Bremsstrahlung of superthermal electrons (the adopted PE could heat them by Compton scattering up to 60 keV). The single-temperature fluid approximation should be rejected

- Scattered photons of the PE soft tail. Those from $1 - 60$ keV range scattered toward the observer could provide an isotropic luminosity equivalent of order 10^{49} erg/s, varying on the curvature delay time scale.

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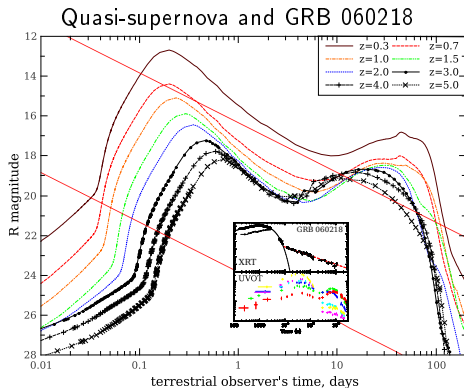
Quasi-Supernova

An extreme case: TE does not escape through the inner boundary, $\mathcal{H}_{\nu,in} = 0$.

▶ **Total peak luminosity** $\sim 10^{49}$ erg/s, X-rays unaffected ($\Rightarrow$ depend mostly on gamma-rays); in optics: **a bright flash** (like a shock breakout) $\rightarrow$ **a long bump/plateau**.

▶ **Expansion velocity** $\sim 6.5 \cdot 10^4$ km/s. A very energetic supernova.

Quasi-supernova and GRB 060218

terrestrial observer's time, days

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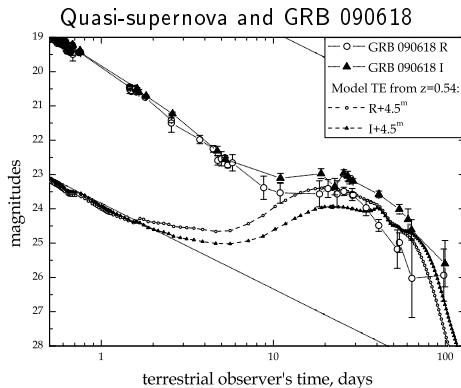▶ **Expansion velocity** $\sim$ $6.5 \cdot 10^4$ km/s. A very energetic supernova.

Quasi-supernova and GRB 090618

terrestrial observer's time, days

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▶ **Similar double-bumped** light curves for GRB 060218 (sn2006aj) (*Campana et al. 2006*). Also reported an X-ray blackbody component with a plateau of $\geqslant 3000$ s duraion.

▶ QSn – nonphysical in 1D, but illustrates **the importance of radiation** around an opacity jump (may be natural in 2D or 3D cases, near surfaces dividing hot and cold dense matter, e.g. jet channel walls).

Quasi-supernova and GRB 060218
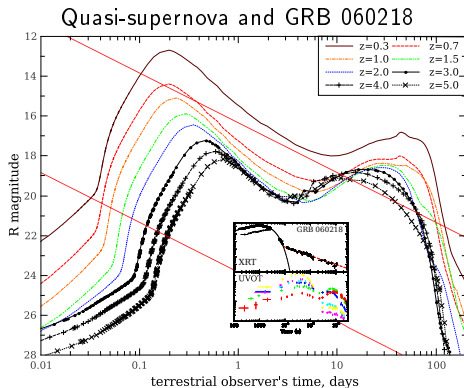
Quasi-Supernova

▶ **A curious consequence** for the GRB-SN connection and central engine theory:

as the sn-bump is allowed to originate in the environment (e.g. due to an explosion driven by radiation),

it removes the necessity for the central engine of the collimated 'failed supernova' outflow, to launch a widespread 'successful' one as well. The latter occurs outside.

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Conclusions

- Massive structures of circumstellar matter $\Leftrightarrow$ **detectable Thermal Emission**, plateaus, bumps, irregularities

- A possibility of off-center supernova-like explosions $\Rightarrow$ a way to explain the GRB-SN connection without placing constraints on GRB central engine.

- An important role of radiation $\Rightarrow$ a necessity in self-consistent relativistic multidimensional **Radiation** hydrodynamics codes.

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Thank you for your attention!