KATHOLIEKE UNIVERSITEIT LEUVEN

A multidimensional numerical approach on energy injection in GRB afterglows

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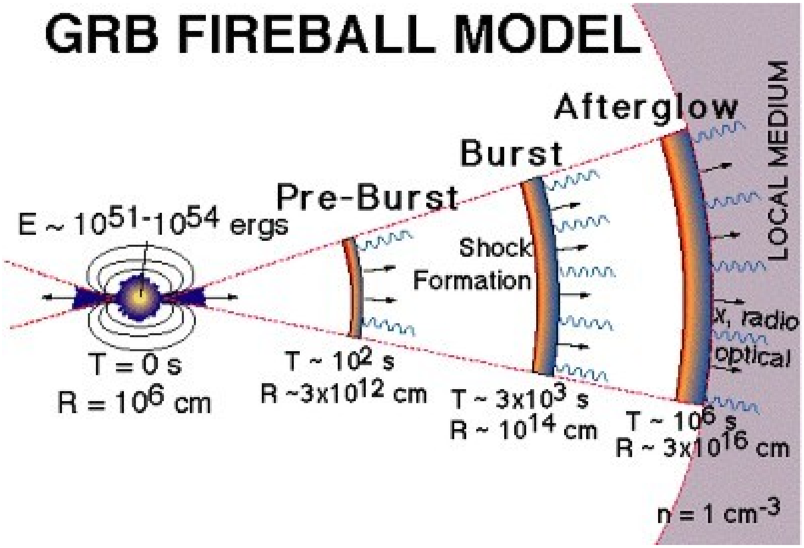
Outline

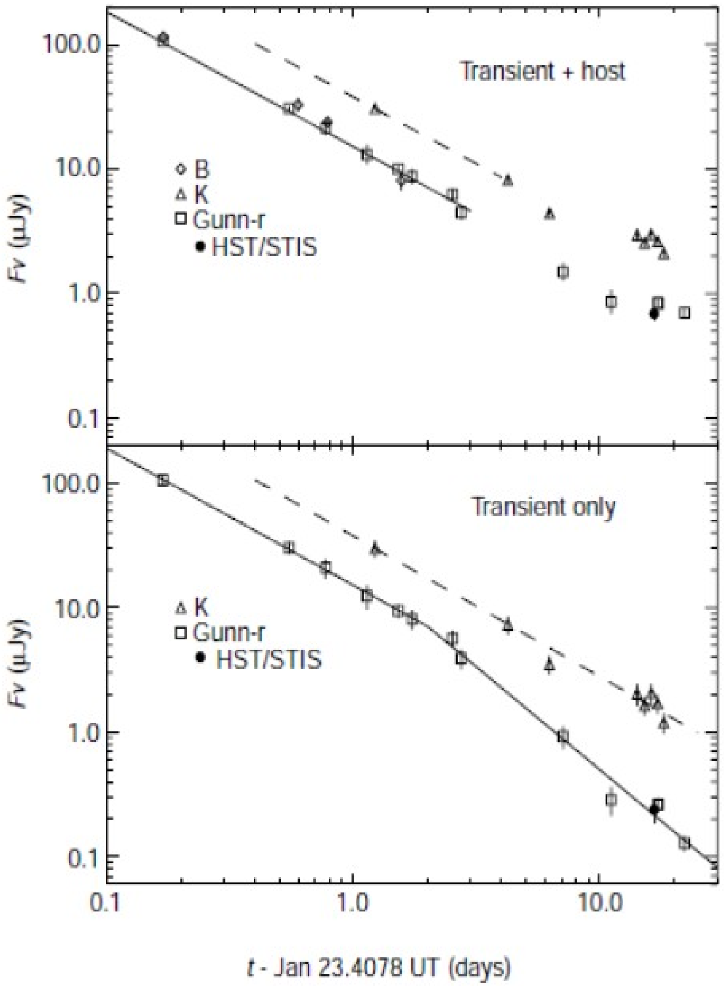
- **Introduction**
  GRBs, afterglows, shell collisions, flares

- **1D model**
  Dynamical simulations and light curves

- **2D model**
  Dynamical effects of the collision, energy distribution, lateral spreading
  efficiency of the jet

Introduction

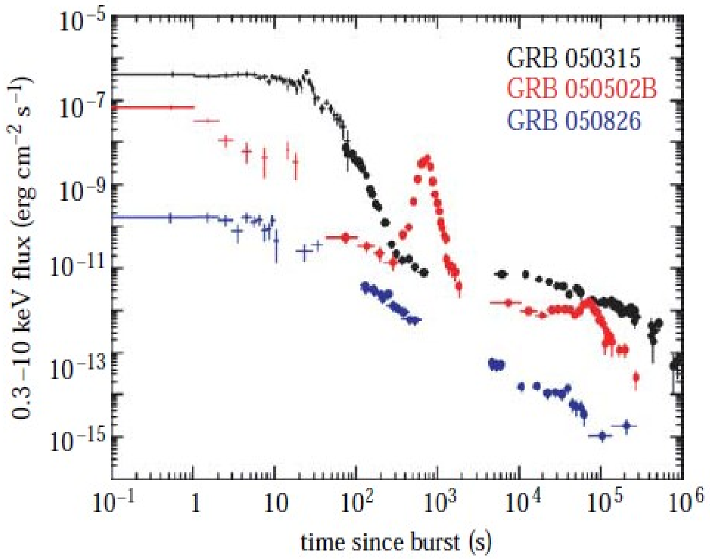




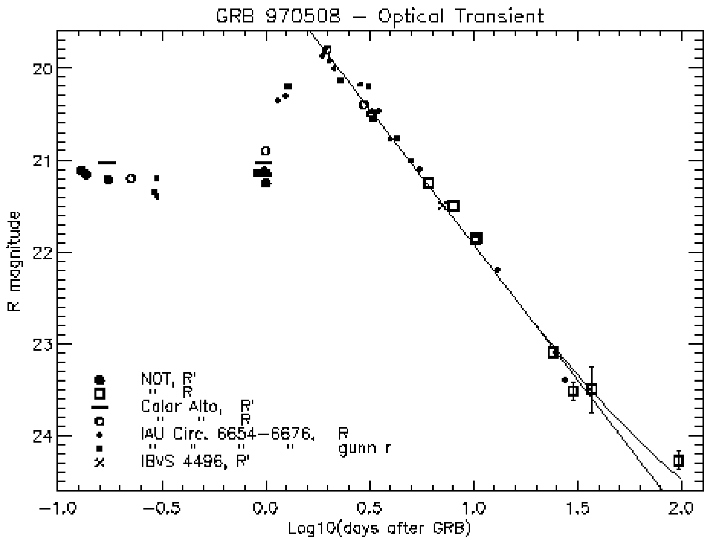
- Progenitors
  Binary merger (Narayan 1992)
  Collapsing massive star (Woosley 2003)

- Steepening of the light curve implies a jet-like structure

Introduction



N. Gehrels 2007



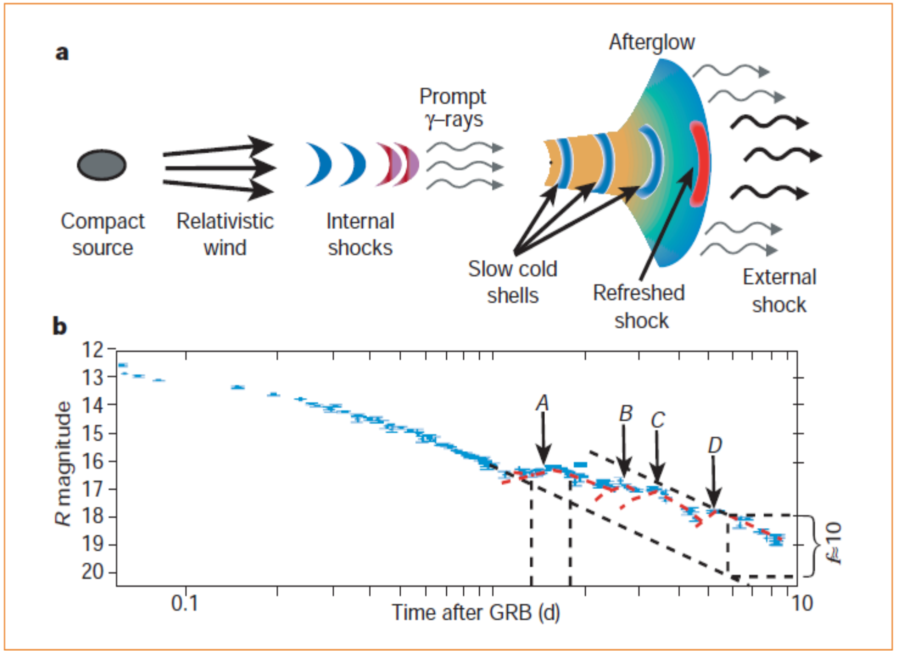
H. Pedersen 1997

- Flares in the afterglow indicate a late central engine activity.
- Different characteristics of the flares suggest that several mechanisms can produce flares.

Introduction

Energy injection to the external shock. A refreshed shock model.

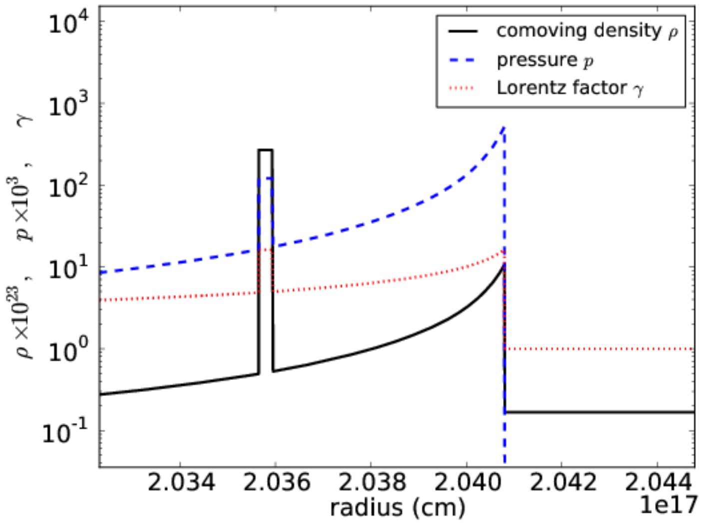
- Refreshed shocks arise when inner shells catch up with the afterglow shock
- Each collision causes a rebrightening in the afterglow light curve.
- After the collision the afterglow resumes its original decay slope.
- Long duration flare $\Delta t < t$

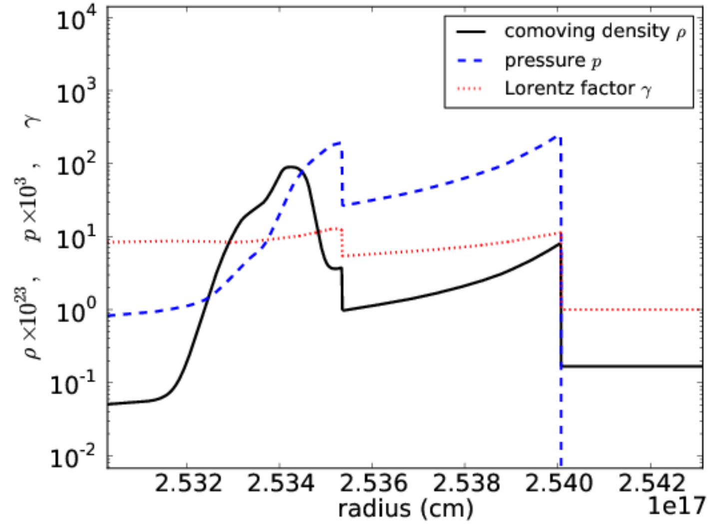


J. Granot 2003

1D model

Dynamical simulation



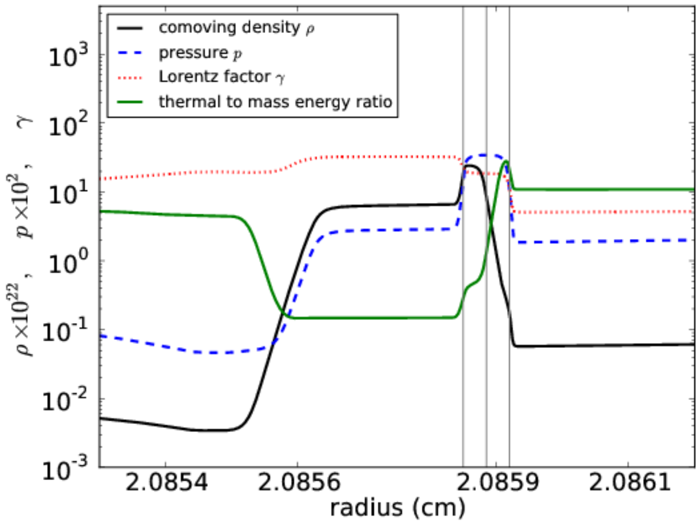


- External shock descried by the BM self similar solution
- The second shell taken as cold and ultra-relativistic with Δt=1000 sec placed in distance ΔR=10^{14} cm behind the external shock.

- Size of the domain [0.01, 10] x 10^{18} cm
- 240 cells at the coarsest level of refinement

- We use 22 levels of refinement leading to an effective resolution of 5 x 10^8 cells.

1D model



- At the position of the **forward shock**

$$n_2 / n_1 = 7.8$$
$$p_2 / p_1 = 10$$

- At the position of the **reverse shock**

$$n_3 / n_4 = 5.5$$
$$p_3 / p_4 = 12.3$$

The forward shock while propagating into the external shell matter increases its thermal energy while at the same time a reverse shock traverses the second shell.

We consider this energy injection into the second shell to produce the flares in the afterglow

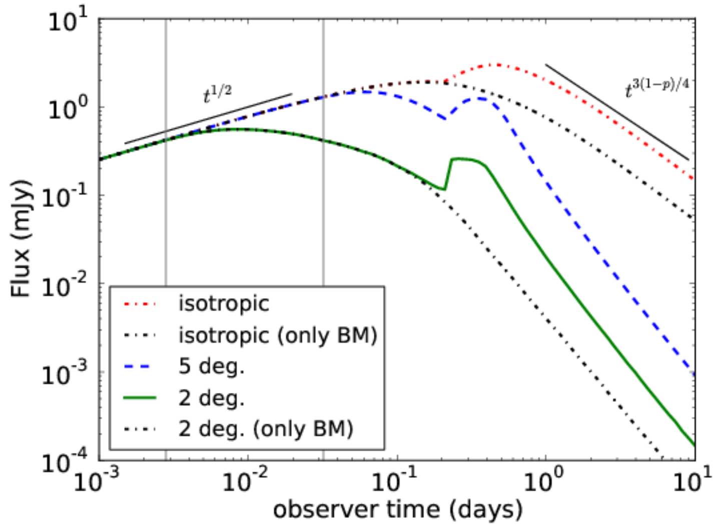
1D model

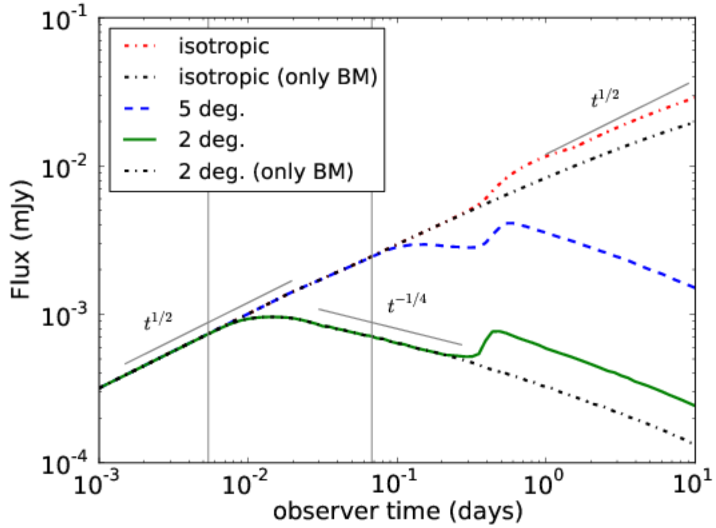
Optical and radio Light curves

- A fraction of the total thermal energy behind the shock goes to particle acceleration and another one to the generation of the magnetic field.

$$\varepsilon_E = 0.1$$
$$\varepsilon_B = 0.01$$
$$p = 2.5$$

- We see a rebrightening for spherical explosion while for small a small opening angle jet a more flare-like behavior is observed.



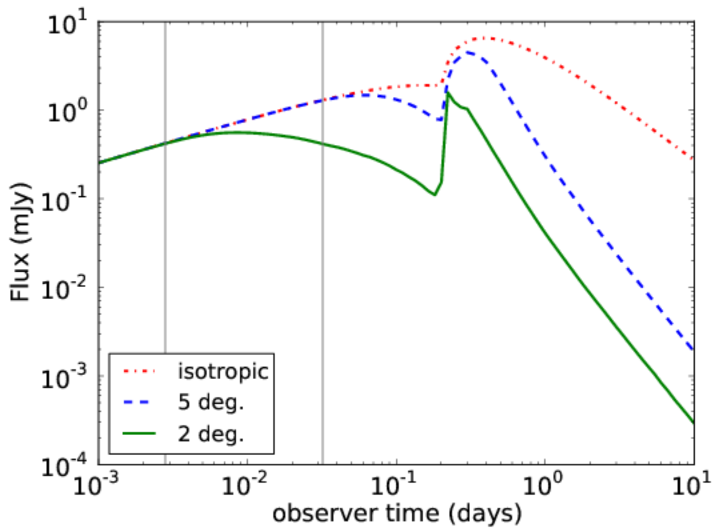


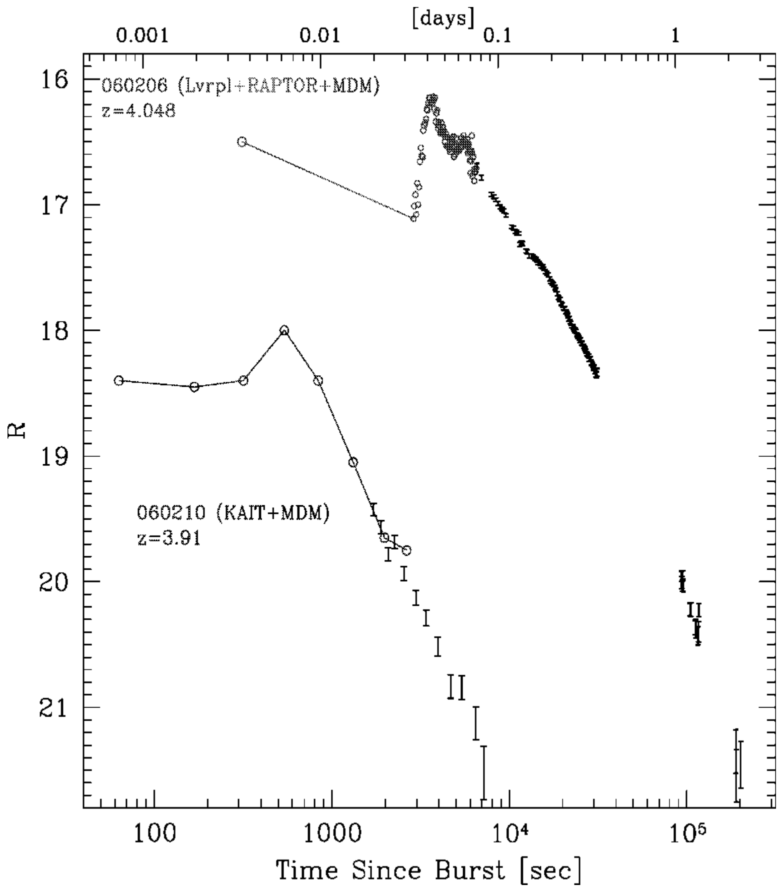
1D model

Comparing with observation.

Initial conditions for the second shell

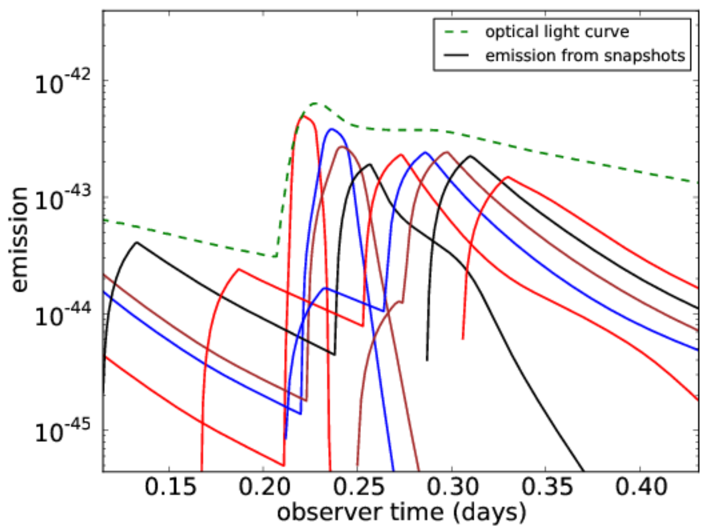
$\Gamma = 46$, $E = 2 \times 10^{52}$ erg
$\rho_{sh} = E / (4\pi\Gamma^2\delta c^2)$
$p = 5\times10^{-2}\rho_{sh}$

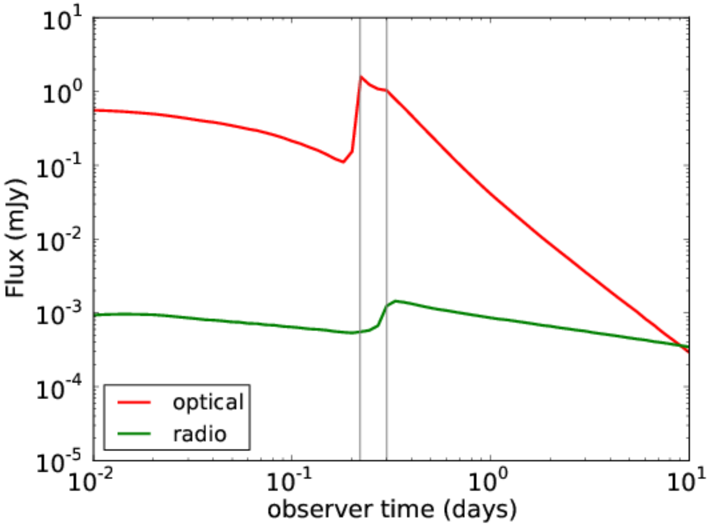




Stanek 2007

1D model

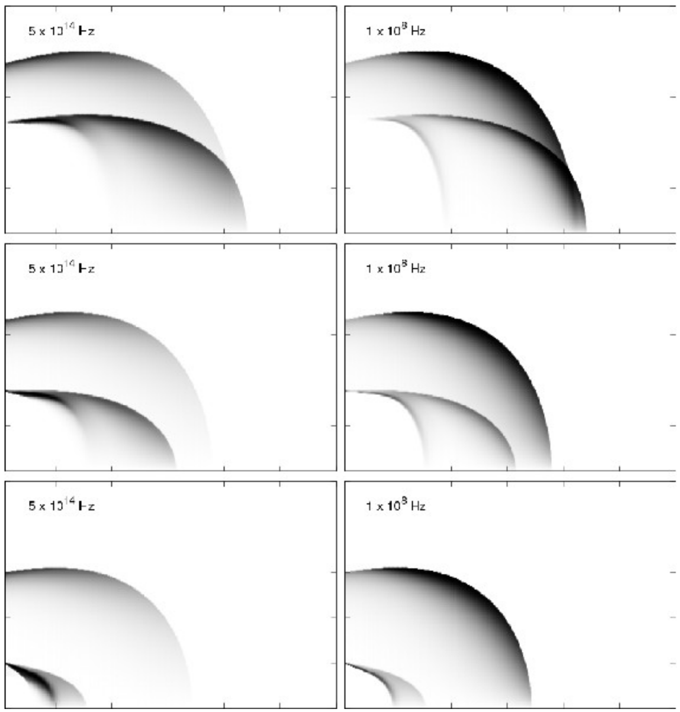


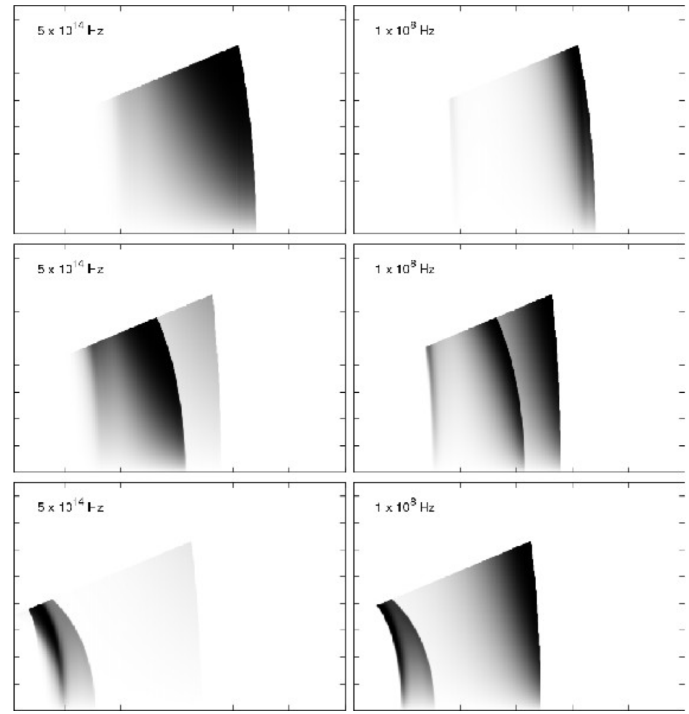


Four stages of the flare

- Sudden rise (forward-reverse emission)
- Steep decay (reverse exits the second shell)
- Constant flux (forward shock moves into the BM matter)
- Steep decay (refreshed shock propagates into ISM)

1D model



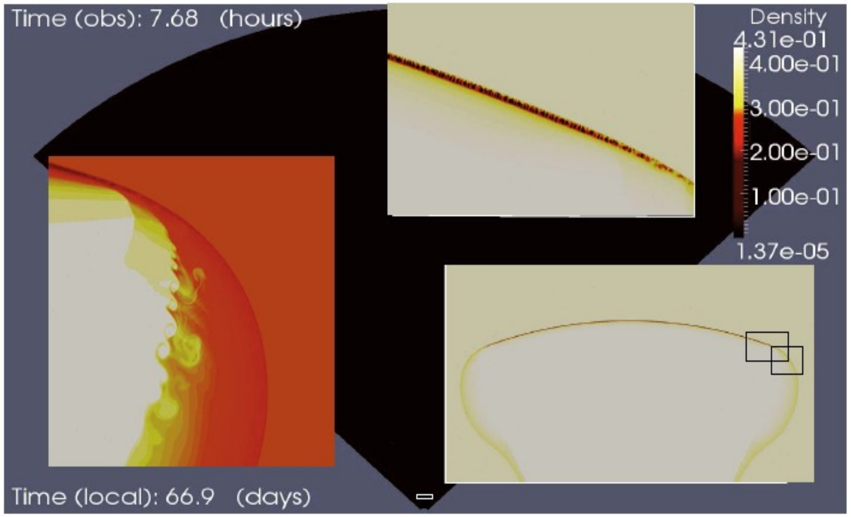


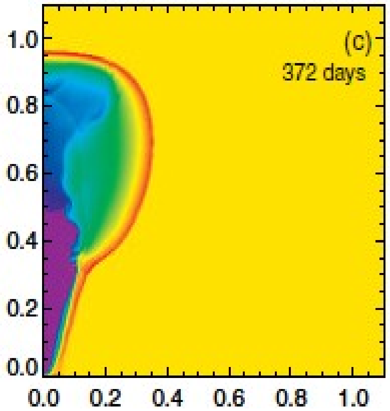
Below the self absorption frequency the jet is optically thick to radio emission and the flare can only be seen after the merger has completed.

2D model

- How important is the lateral spreading for small opening angle GRB jets?
- Can the collision of the shells affect the dynamics in the angular direction?

Significant spreading is predicted from analytical models (Rhoads 1999, Sari et al. 1999) while numerical simulations show more modest expansion (Zhang & MacFadyen 2009, Meliani et al. 2010, de Colle 2012)





Zhang and MacFadyen 2009

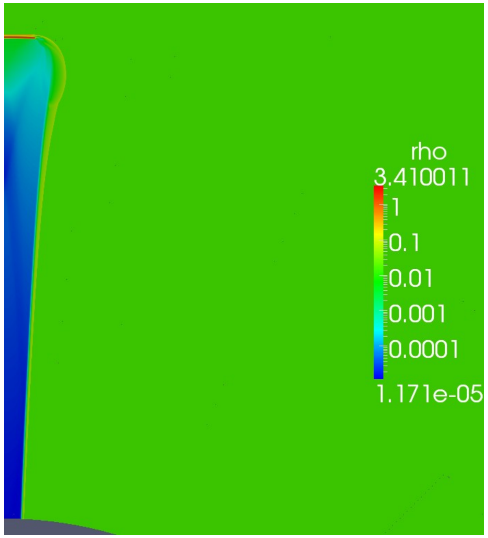
Meliani 2010

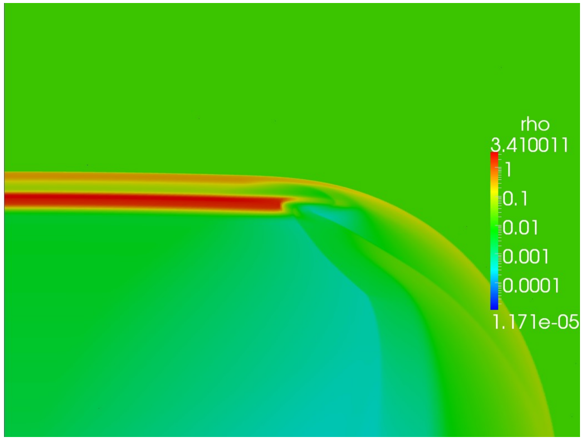
2D model

Initial setup

θ_h = 2 degrees half opening angle of the jet
$\Gamma_{BM} = \Gamma_{shell} = 23$
$E_{BM} = E_{shell} = 10^{52}$ erg

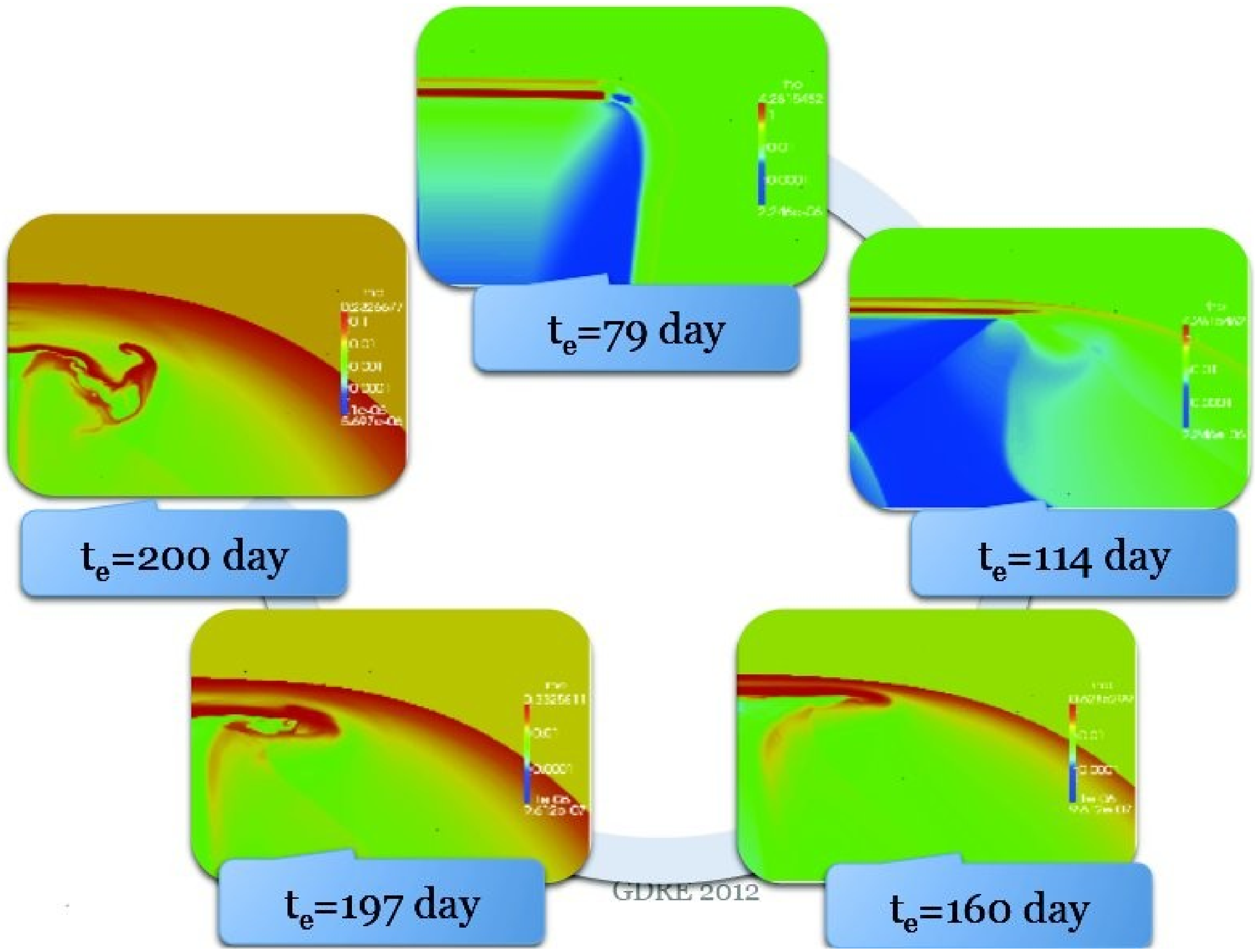
We use a spherical grid of size **[0.01, 1] x 10^{19} cm** and **[0, π/2] radians** and a maximum of **10 levels of refinement** leading to an effective resolution of **2.46579 x 10^6 and 14336 cells** in the radial and angular direction respectively.





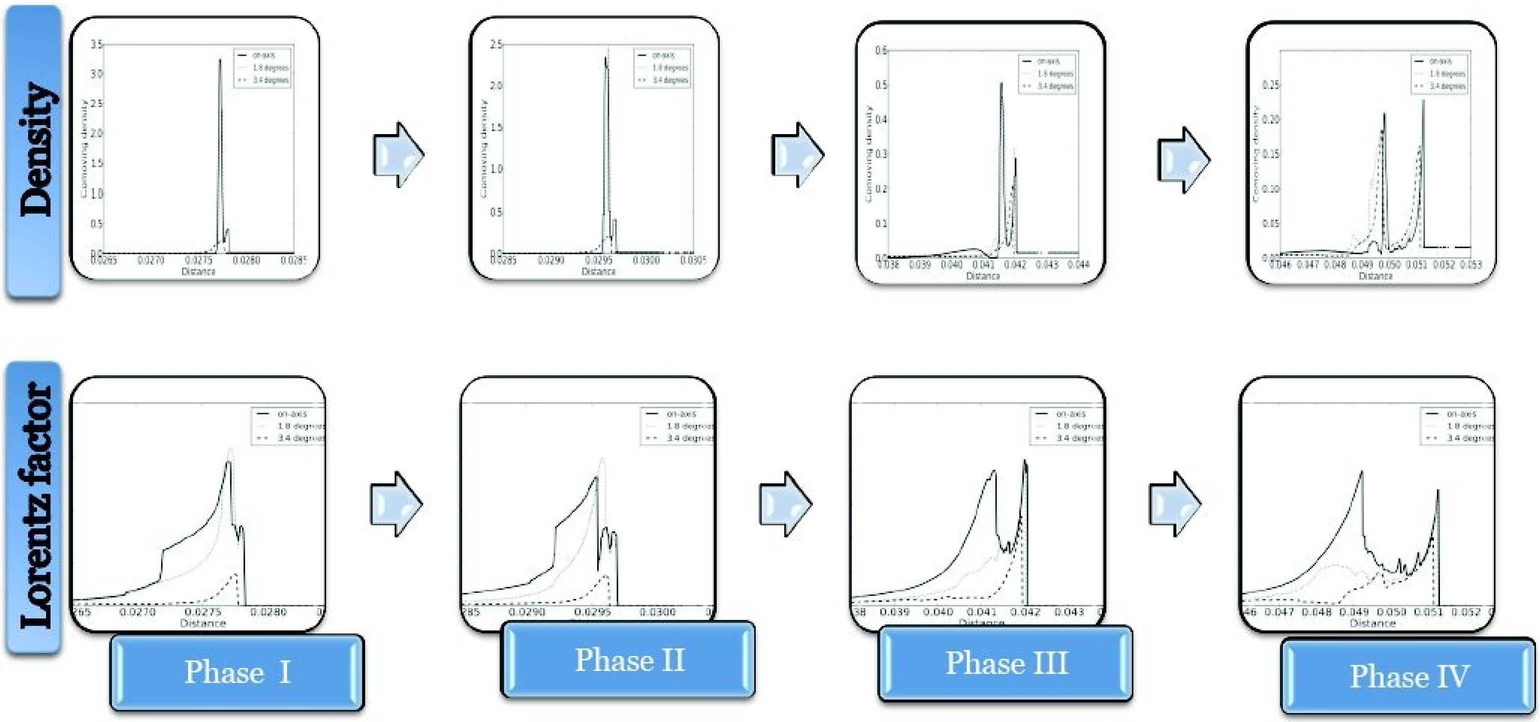
t_{local} = 90 days

Comoving density in the vicinity of the two shells

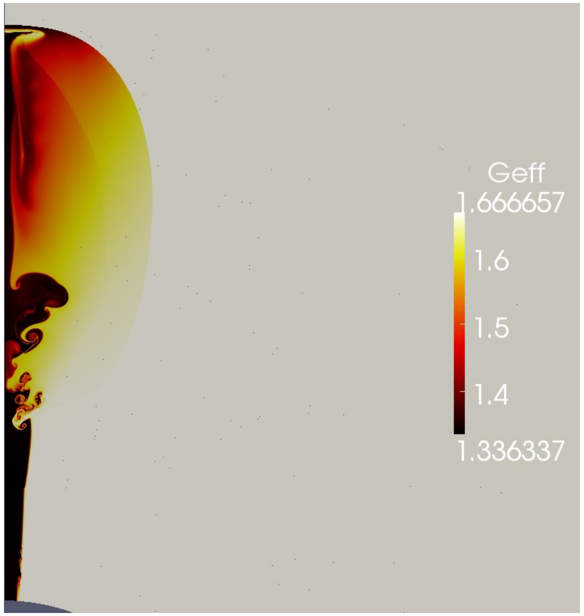


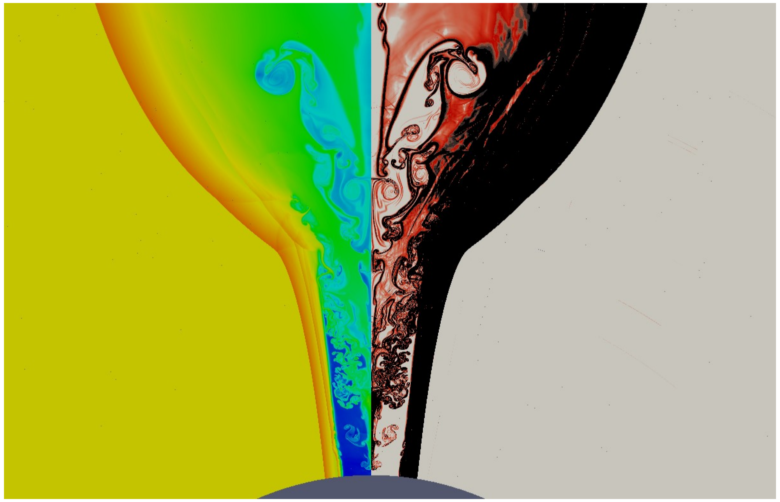
Global evolution of the jet

- Angular variation of the fluid properties.
- Angle dependent collision time.



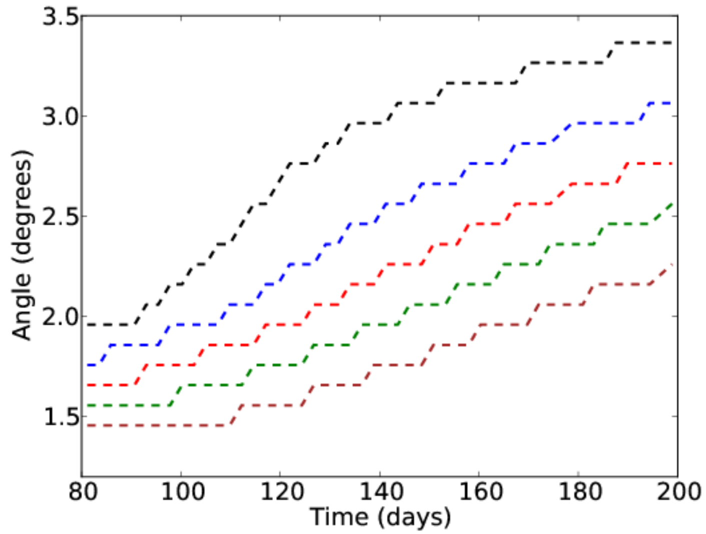
2D model

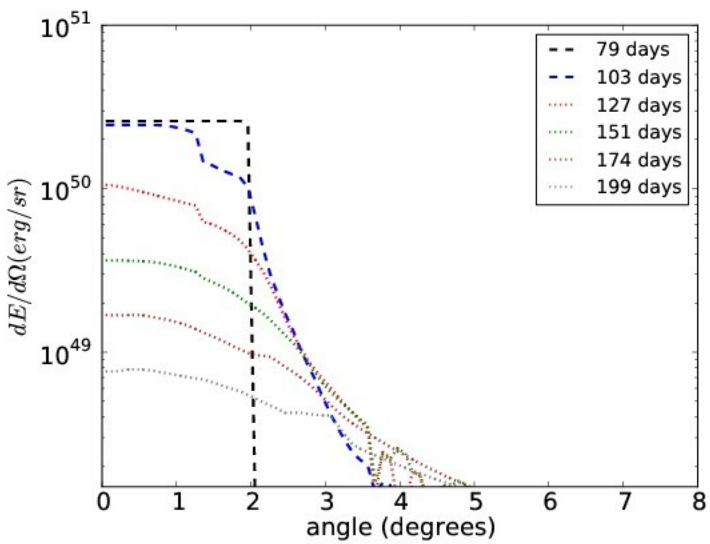




- The external shock is highly efficient in thermalizing the shocked ISM matter $\Gamma_{eff} = 4/3$, while for higher angles the fluid remains Newtonian, $\Gamma_{eff} = 5/3$
- The base of the jet is dominated by Kelvin-Helmholtz instabilities at later times

2D model





Evolution of the jet opening angle which contains 90% (black line), 80% (blue line), 70% (red line), 60% (green line) and 50% (brown line) of the initial energy.

Energy density distribution with the angle for different local emission times.

Conclusions

- Strong rebrightenings and flares can appear in optical and radio light curves from energy injection in the external shock.

- The parameters of the second shell strongly influence the shape of the flare/rebrightening.

- The observed chromaticity of the flare can be interpreted as a direct result of the synchrotron-self absorption (ssa) mechanism.

- The lateral spreading of the jet appears to be small throughout the collision process but is nevertheless strongly influenced by the second shell.