GRB Jets and Early Afterglows

Observational constraints on the magnetization of GRB fireballs

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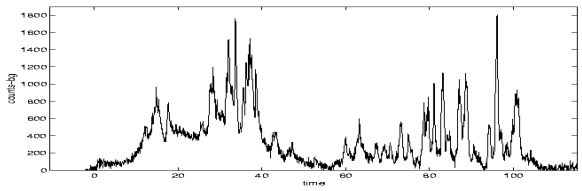
Talk Outline

- GRBs
  - Prompt emission, Optical flash, Afterglow
- Relativistic motion
  - Essential element in fireball model
  - Magnetized / Poynting flux dominated outflow
- Magnetization
  - Afterglow Modeling
  - SSC Emission
  - Polarimetry

Gamma-ray bursts

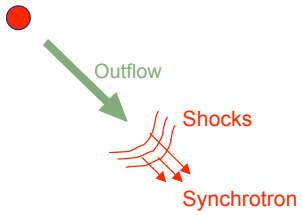
- Intense flashes of 0.1-1MeV photons
  - Arriving from random directions in the sky
  - A few events per day
  - Light curves: highly variable: compact sources



Fireball Model

Synchrotron Shock model

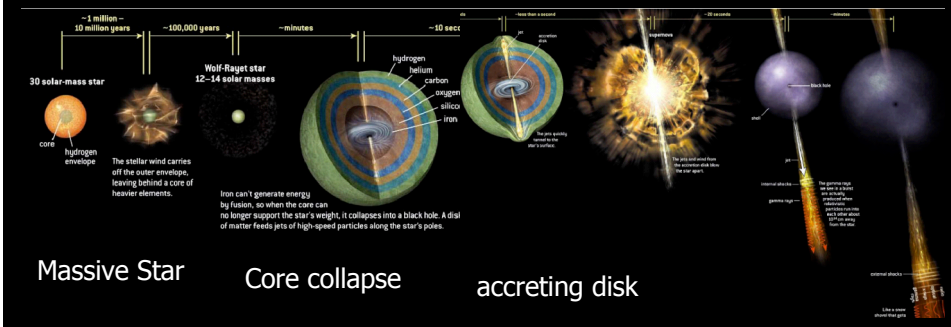
1) Relativistic outflow from a compact source
   - death of massive stars, compact stellar mergers



2) Shock formation at large radii
   - Electron acceleration in shocks

3) Synchrotron/IC from electrons

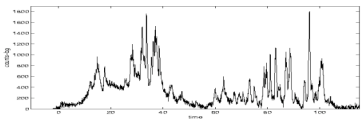
Collapsar Model for Long GRBs



Massive Star Core collapse accreting disk relativistic jet

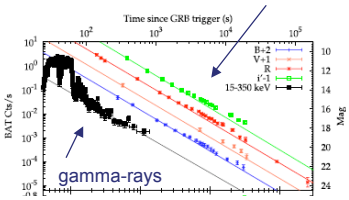
two main emission components of GRBs

- Prompt gamma-rays
  - light curves: highly variable
  - T < a few ten-hundred sec

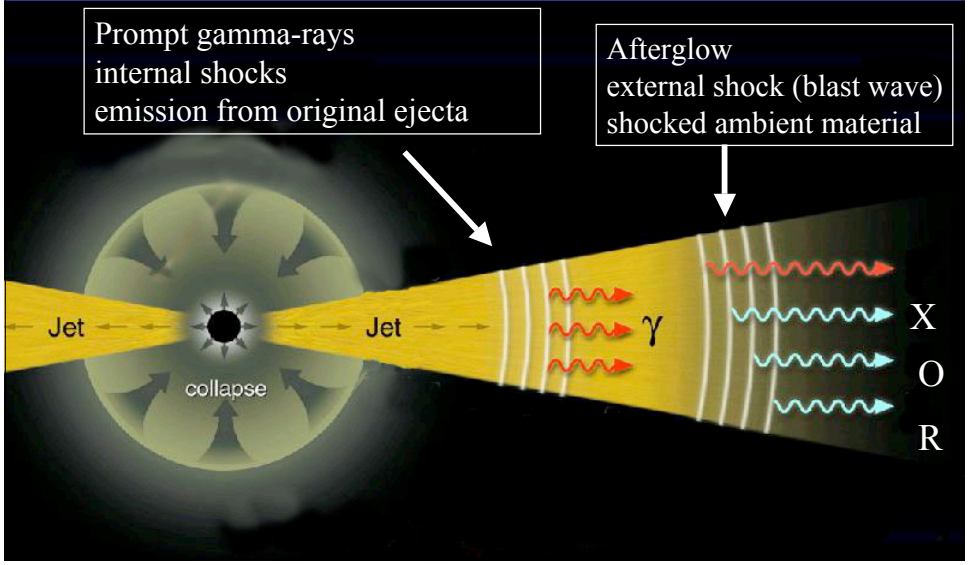


- Afterglow: discovered in 1997
  - X-ray, opt, radio counterparts
  - light curves: smooth, power-laws
  - lasts much longer (~ yr)

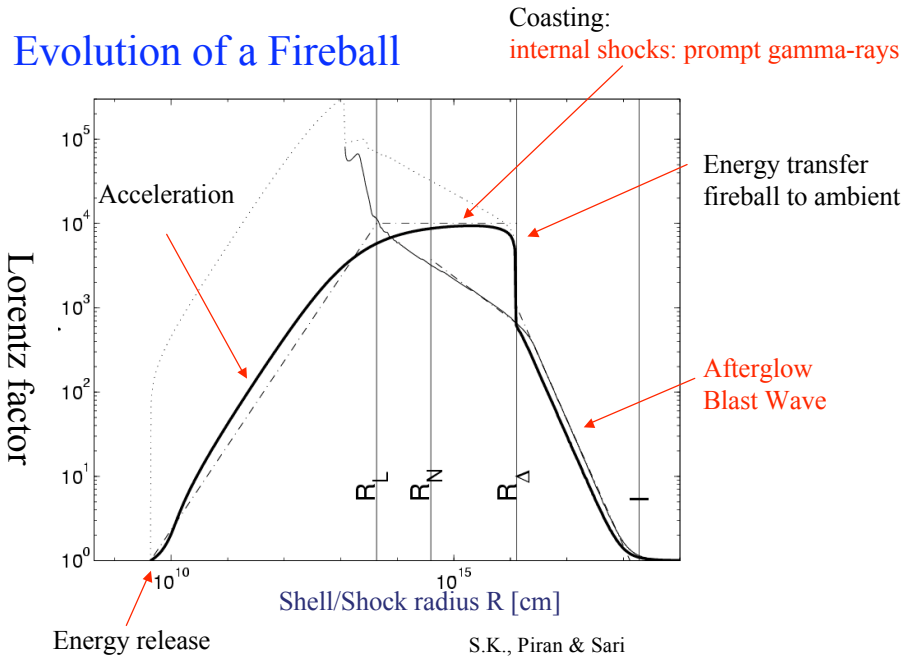
opt afterglow



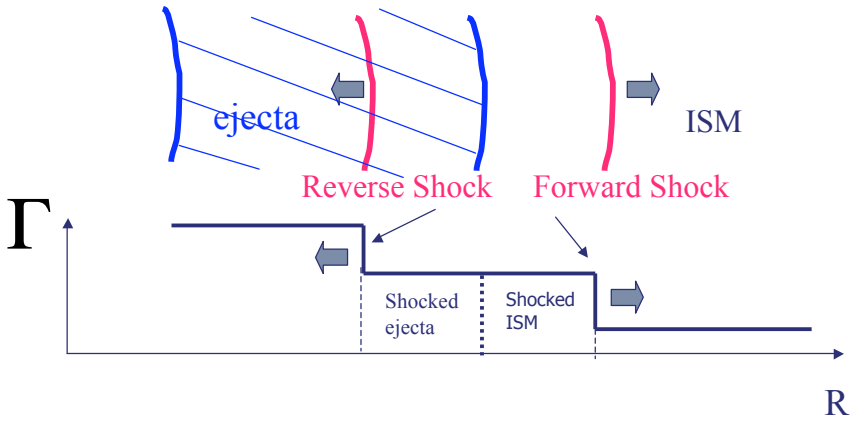
Internal-External shock model



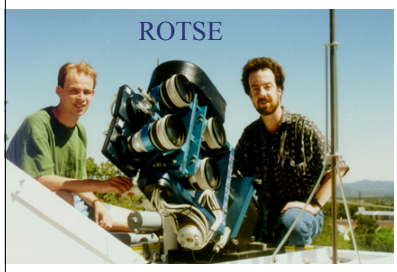
Evolution of a Fireball

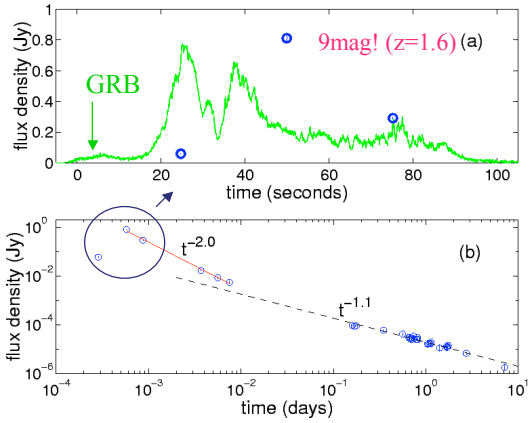


deceleration and energy transfer



Optical Flash : GRB 990123





(Akerlof et al. 1999; Meszaros&Rees 1997; Sari & Piran 1999; S.K 2000)

main emission components: close look

- Prompt gamma-rays
  - T < a few ten-hundred sec
  - emission from ejecta

Optical flash: Reverse Shock
short-lived
emission from ejecta

- Afterglow: Forward shock
  - emission from ambient medium

"Early afterglow"
Reverse shock/forward shock emission right after GRBs
Robotic telescopes

Relativistic motion

essential assumption in fireball model

- Huge amount of energy in a compact source
  Optically thick sources expected: e+e- pairs

- Observations: optically thin source
  - Non-thermal spectrum with a high energy tail

$$\Gamma > 100$$

larger source volume allowed
less photons with high energies in comoving frame

Observational supports of relativistic motion

- Optical depth for high energy photons

  e.g. Lithwick&Sari; Fermi collaboration

- Onset of Afterglow: a few hundred sec: $\Gamma \sim$ a few hundred

$$\Gamma = \left(\frac{E}{\rho c^5 t_{on}^3} \right)^{1/8}$$

- Radio Afterglow
  - quenching of scintillation
  - superluminal motion
- Thermal emission component in GRB

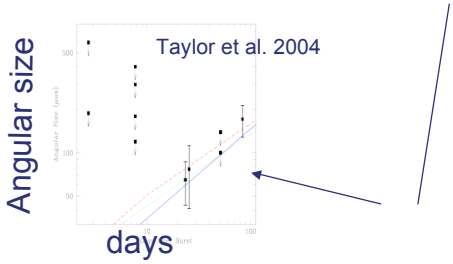
  Pe'er, Ryde, Wijers et al.

- **Quenching of scintillation (diffractive)**
  - 4 weeks after GRB 970508
  - This implies a size R ~ 10^17cm
  - Expansion speed: ~c
- Diffractive scintillation
  - caused by interference between rays diffracted by small-scale irregularities in ionized ISM
  - occurs only when the source size is smaller than a characteristic size (diffractive angle).

Waxman et al. 1998; Frail et al. 2000

Direct measurement GRB030329 (bright, nearby)

- **V**ery **L**arge **B**aseline **I**nterferometry
  - Afterglow images resolved
    25 and 83 days after GRB
- The observed expansion velocity: 3c-5c
  - Superluminal motion
  - Good agreement with theoretical predictions



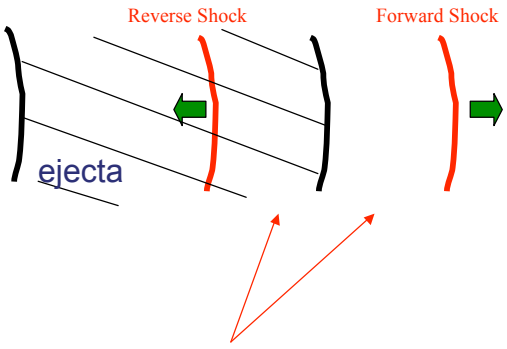
Big problem

- How to accelerate/collimate jets?
  - gamma>100, E=10^52 ergs

- Poynting flux dominated jets?
  - attractive model
  - AGNs

- observational constraints on the magnetization of GRB jets?
  - Early afterglow model
  - SSC component
  - polarimetry

Early Afterglow Modeling



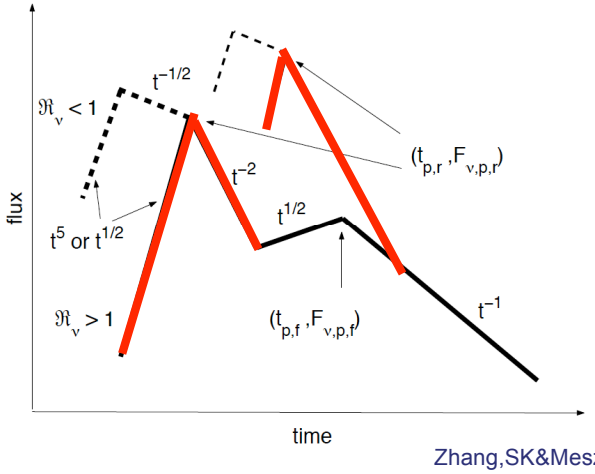
Different magnetization?

Optical flash: Reverse shock emission
Afterglow: forward shock emission

5

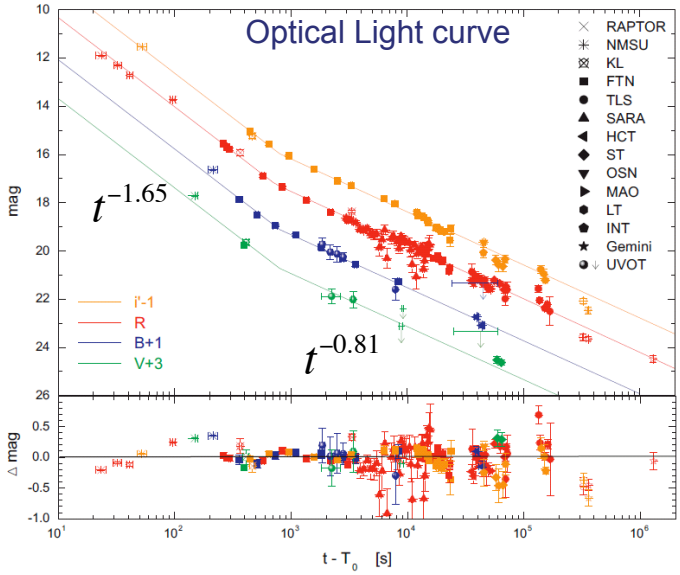
the peak times and fluxes

the ration of magnetic energy densities in the two shock regions U_B



Zhang,SK&Meszaros

GRB 061126



Gomboc, SK, Guidorzi, et al. 2008

GRB 990123, GRB 021211, GRB 061126

Magnetic energy ratio: Reverse and Forward shocks

$$U_{B,reverse} / U_{B,foward} = 20 - 30$$

(Zhang, SK,&Meszaros; Kumar&Panaitescu; Gomboc et al.)

Afterglow broad band modeling

$$\varepsilon_{B,forward} = 10^{-4} - 10^{-2}$$

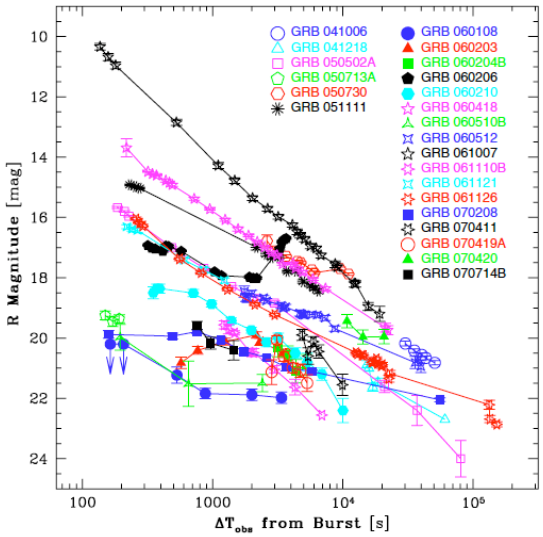
magnetic energy density
expressed as a fraction of the equipartition value (shock energy)

Reverse shock region
higher magnetization, still a baryonic jet

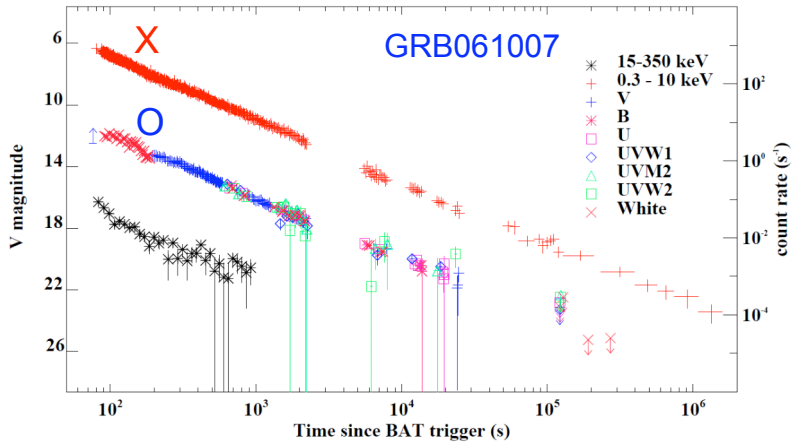
- Fireball model predicts
  - early optical emission from reverse shocks

- A large fraction of events: No optical flas

Light Curves of early optical afterglow



Melandri et al. LT/FTN/FTS



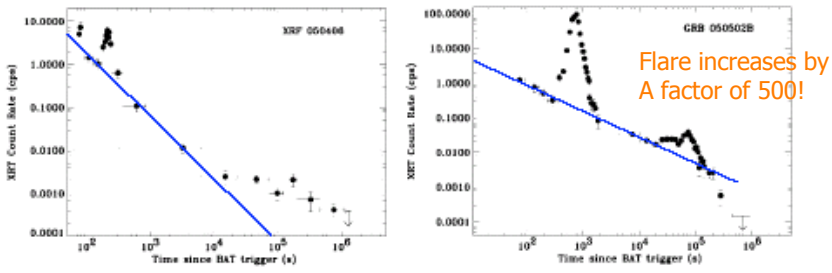
Schady et al.(06)

- A large fraction of events: No optical flash
  - Emitted at even lower frequencies?
  - Dust extinction in host galaxies?
  - Emitted at high frequencies via SSC?
  - Poynting flux dominated outflow?

Each jet: different magnetization?

Synchrotron Self-Invese Compton (SSC) and X-ray flares

X-ray flares: flare events in early X-ray afterglow



Burrows et al. 2005

If 1st order IC is in X-ray $h\nu_X \sim 5$ keV
the comoving photon energy of the 1st IC is $h\nu'_X = h\nu/\Gamma \sim 50$ eV

KN does not suppress the 2nd IC as long as $\gamma_m < m_e c^2/h\nu'_X \sim 100\Gamma$

2nd IC: 10-100MeV range

$$x \equiv \frac{L_{IC,1st}}{L_{syn}} = \frac{U_{syn}}{U_B} = \eta\frac{U_e}{U_B}\left(1+\frac{U_{IC,1st}}{U_{syn}}+\frac{U_{IC,2nd}}{U_{syn}}\right)^{-1} = \eta\frac{\epsilon_e}{\epsilon_B}\left(1+x+x^2\right)^{-1}$$
$$x_2 \equiv \frac{L_{IC,2nd}}{L_{syn}} = \frac{U_{IC,1st}}{U_B} = \frac{U_{IC,1st}}{U_{syn}}\frac{U_{syn}}{U_B} = x^2$$

$$x = \begin{cases} (\eta\epsilon_e/\epsilon_B) & \text{if } (\eta\epsilon_e/\epsilon_B) \ll 1 \\ (\eta\epsilon_e/\epsilon_B)^{1/3} & \text{if } (\eta\epsilon_e/\epsilon_B) \gg 1 \end{cases}$$

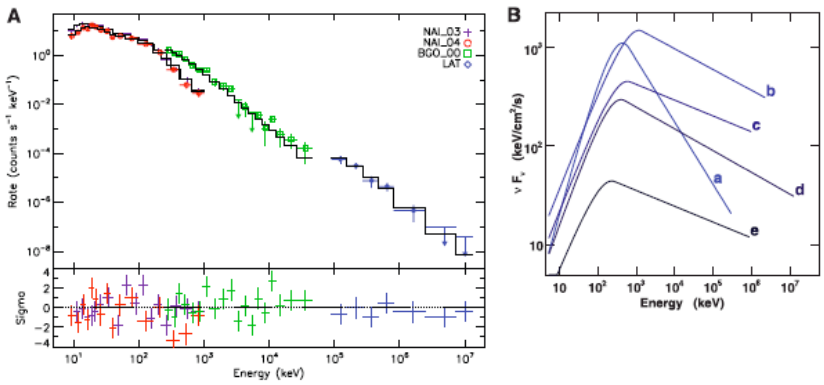
sk,zhang, meszaros&burrows

SSC model does not work to explain X-ray flares

- GRB 050502b: brightens by a factor of several hundreds
  - Compton parameter: x~100 $\varepsilon_e/\varepsilon_B > 10^8$
  - with plausible values of the other parameters: SSC well above X-ray band

- the feature of flares too sharp: $\Delta t/t < 1$
- multiple flares observed
- Fermi: no feature around 10-100 MeV

- Late time internal shocks



GRB 080916C : Fermi Collaborations 2009

The lack of SSC component

- High magnetization of the fireball: magnetized fireball?

  Compton parameter $x = \left(\varepsilon_e / \varepsilon_B\right)^X$

- the SSC is above the Fermi band $E_p^{SSC} \sim \gamma_m^2 E_p^{syn}$

  $\gamma_m \sim \frac{m_p}{m_e} \sim 1800$

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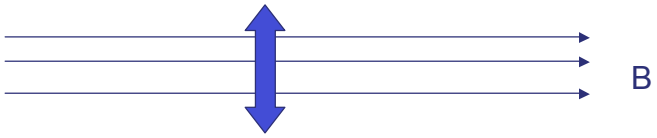
not so many high energy detections by Fermi

- pair-creation $\Gamma \geq 1000$ GRB 080916C
  - general cases: sources optically thick for high energy photons?

- Synchrotron Emission +ordered B-fields
  - linear polarization
    - a large fraction of waves oriented in a single direction
  - Polarization: the smoking gun of synchrotron emission
  - Large polarization signal: large scale magnetic fields



Polarization measurements of prompt /optical flash needed to investigate GRB ejecta properties

Controversial results: prompt gamma-ray (Coburn&Boggs2003)

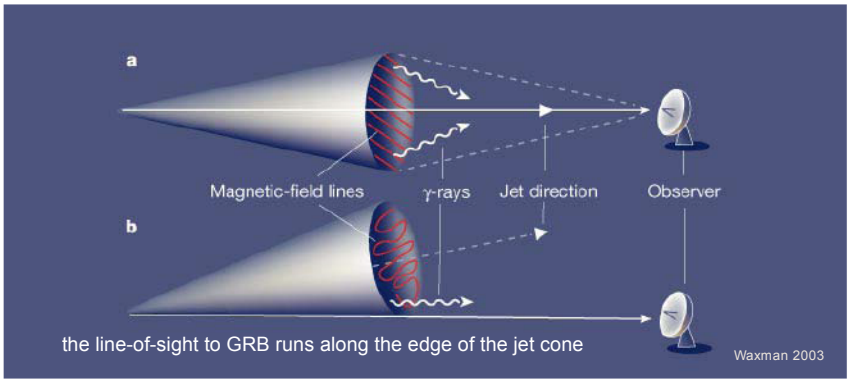
Late (~1day) polarization measurements: jet breaks

First detection:optical
1.7% for GRB 990510
Covino et al. Wijers et al.

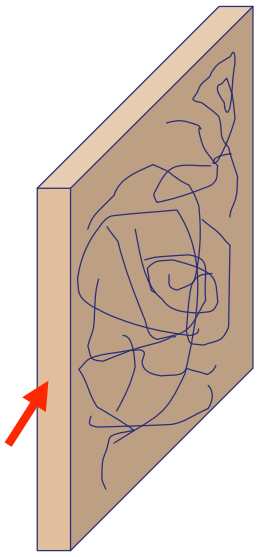
optical upper limit
2.3% GRB 990123
Hjorth et al.

Radio upper limits
19% GRB 980329
8% GRB 980703
Taylor et al.; Frail et al.

two options to produce high polarization



(Sari1999;Gruzinov 1999;Ghisellini&Lazzati1999;Waxman 2003;Granot2003;Nakar et al.2003;Rossi et al. 2004)

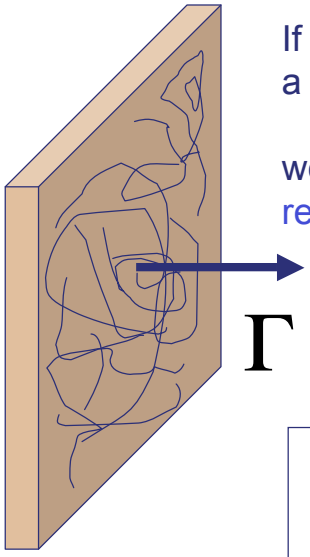


Random Magnetic fields generated by instabilities.

$$B_{//}, \quad B_{\perp}$$

(Medvedev&Loeb1999)

Some degree of alignment if observed edge-on if the emitter is observed edge-on



If the emitter moves with
a relativistic velocity,

we have to take into account the
relativistic aberration of photons.

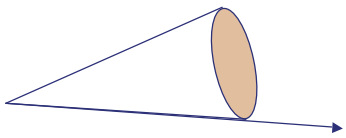
Γ

comoving frame : $\theta' = \pi/2$

$\Rightarrow$ lab frame : $\theta = 1/\Gamma$

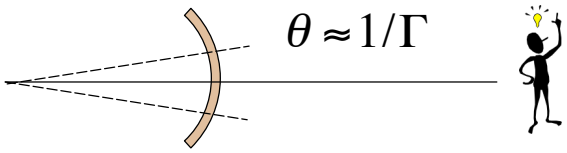
Large Polarization

when the line-of-sight to GRB runs along the edge of the jet cone



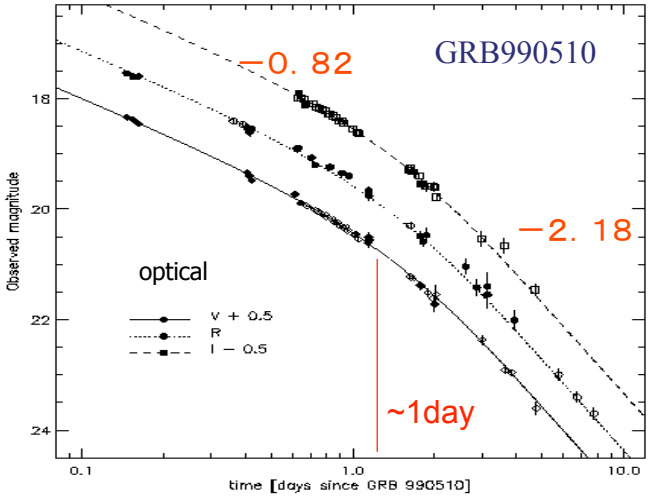
this happens around a jet break

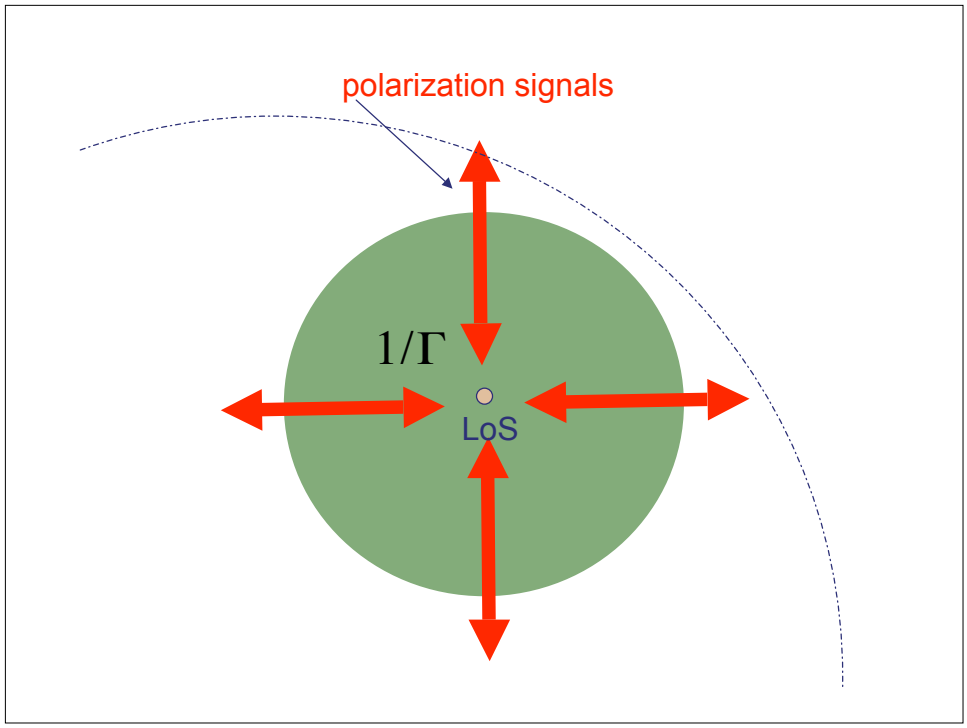
Jet break: seeing the edges

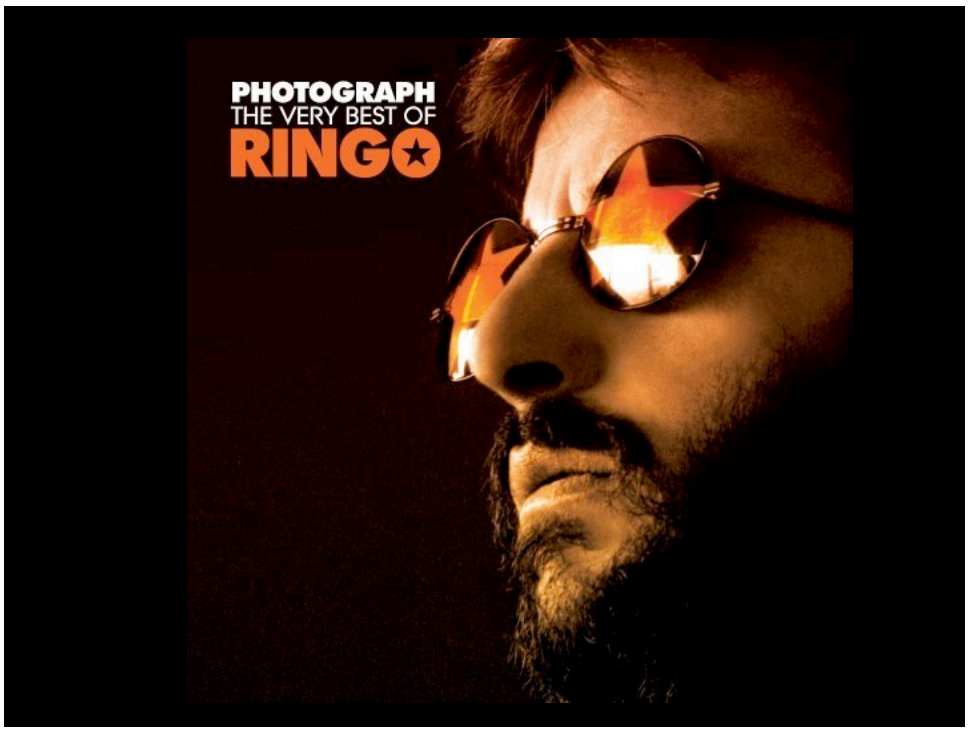


when the emitter (e.g. blast wave) slowed down,
we recognize it is not spherical

- break in optical afterglow light curve



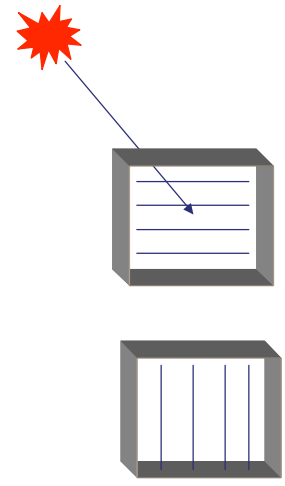

polarization signals
1/Γ
LoS


PHOTOGRAPH
THE VERY BEST OF
RINGO

Early polarization measurements

Liverpool telescope (polarimeter: RINGO)

- 2m robotic telescope at the Canary Island of La Palma, Spain



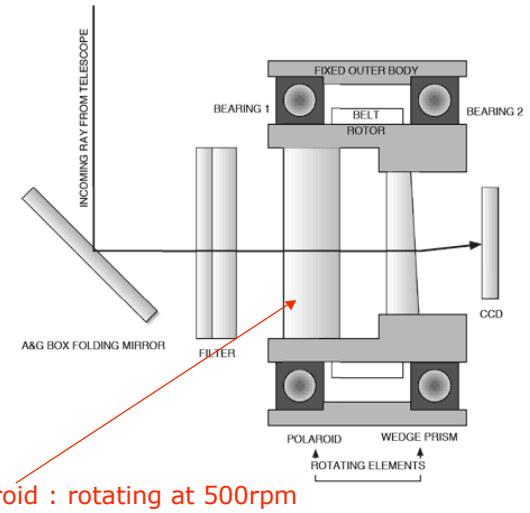
Rotating polarizer by 90 deg

Polarization degree

$$\Pi = \frac{I - I_{\perp}}{I + I_{\perp}}$$

Afterglow luminosity changes very rapidly…

$\Delta m = 0.1$ could produce false 5% polarization

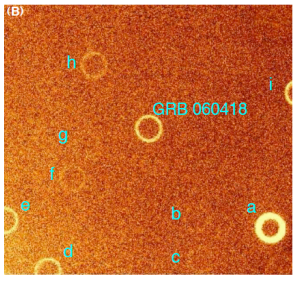


- Polaroid : rotating at 500rpm
- Source is imaged as a small ring, with the polarization signal mapped out around it.

GRB 060418

Afterglow polarization measurement

- 200 sec after GRB trigger
- At the onset of afterglow: 14mag
- bright night: 3/4 full moon
- Polarization: 8% upper limit

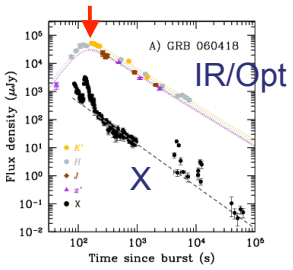


Mundell et al. 2007

8% upper limit at the onset of afterglow

1) No large-scale magnetic fields in the “emitting region”.

2) B-fields suppressed reverse shock and its emission.



we need more observations to settle the issue.

Summary

- How to test / investigate magnetized fireball model?
- Early afterglow modeling
  - higher magnetization in reverse shock region, still baryonic
  - why no optical flashes in many events?
  - low freq? dust extinction? magnetized?
- SSC emission
  - flares in early x-ray afterglow: SSC models does not work
  - no SSC components : prompt/RS: consistent with magnetized outflow
- Early Polarization measurements
  - upper limit 8% at the onset of afterglow
  - no large-scale magnetic fields in fireball
  - magnetic pressure kills reverse shock?