Supernova shock breakout and low-luminosity GRBs

王祥玉

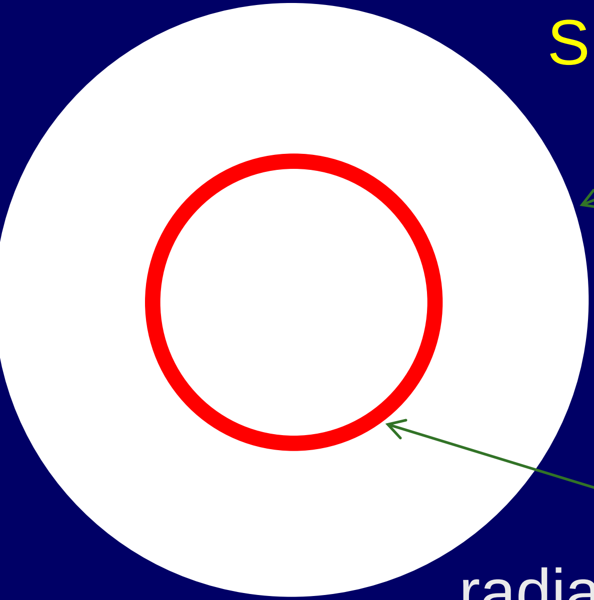
南京大学

SN Shock breakout

Radiation dominated shock:

✓radiation pressure>gas pressure

✓the shock transition is mediated by radiation (Compton scattering)



Shock width = distance to edge （$\tau=c/v$）

Shock breakout

Colgate 1974; Klein&Chevalier 1978; Ensman & Burrows 1992; Blinnikov et al. 1998; Matzner & McKee 1999)

radiation-dominated shock

Predicted shock breakout emission

✓软X射线辐射
✓热辐射
✓持续时间
✓能量

$$T_{\rm se} = 5.55 \times 10^5 \left(\frac{\kappa}{0.34\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-0.10} \left(\frac{\rho_1}{\rho_*}\right)^{0.070} \times \left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{0.20} \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.052} \times \left(\frac{R_*}{500\ R_\odot}\right)^{-0.54} {\rm K} \quad \left(n = \frac{3}{2}\right),$$

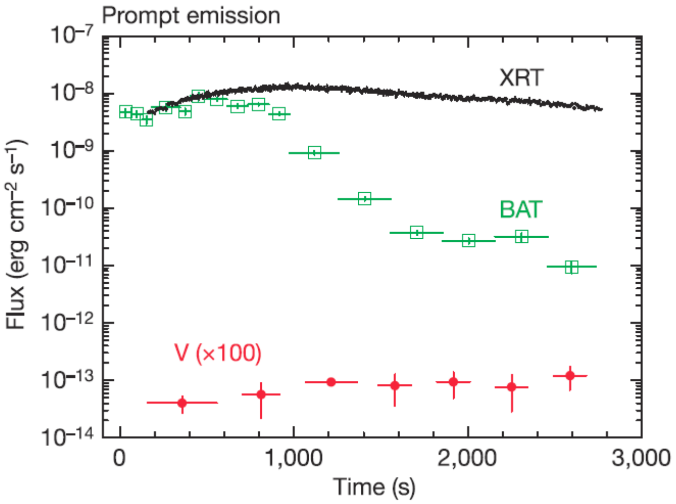
$$T_{\rm se} = 1.31 \times 10^6 \left(\frac{\kappa}{0.34\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-0.14} \left(\frac{\rho_1}{\rho_*}\right)^{0.046} \times \left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{0.18} \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.068} \times \left(\frac{R_*}{50\ R_\odot}\right)^{-0.48} {\rm K} \quad (n = 3)\,.$$

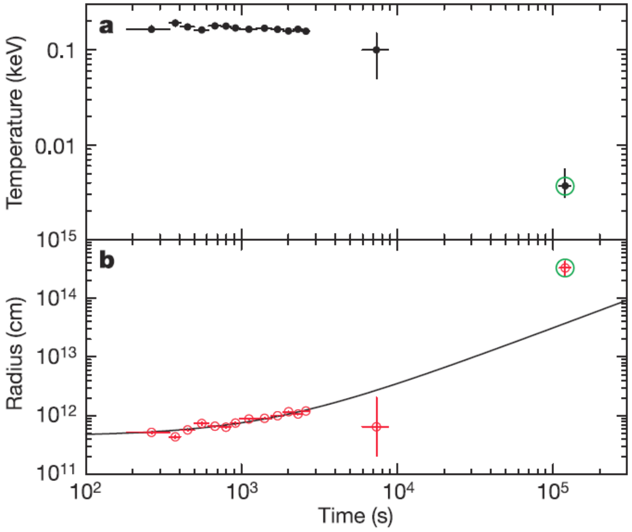
$$E_{\rm se} = 1.7 \times 10^{48} \left(\frac{\kappa}{0.34\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-0.87} \left(\frac{\rho_1}{\rho_*}\right)^{-0.086} \times \left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{0.56} \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.44} \times \left(\frac{R_*}{500\ R_\odot}\right)^{1.74} {\rm ergs} \quad \left(n = \frac{3}{2}\right),$$

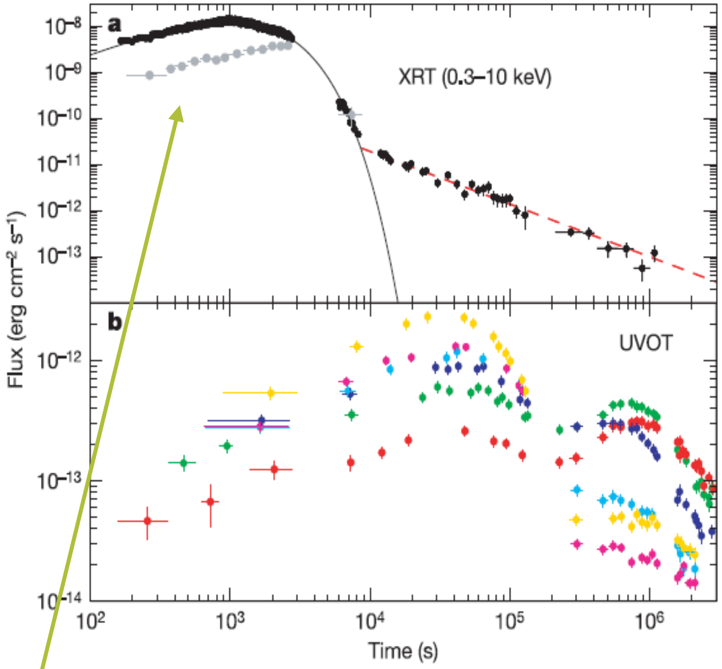
$$E_{\rm se} = 7.6 \times 10^{46} \left(\frac{\kappa}{0.34\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-0.84} \left(\frac{\rho_1}{\rho_*}\right)^{-0.054} \times \left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{0.58} \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.42} \times \left(\frac{R_*}{50\ R_\odot}\right)^{1.68} {\rm ergs} \quad (n = 3)\,.$$

Matzner & McKee 1999

SN2006aj/GRB060218 Campana et al. 06, Nature







- prompt thermal x-ray emission—mildly relativistic SN shock breakout

Waxman, Meszaros, Campana 07

Deriving the shock properties—1) shock breakout radius

characteristic radius of emitting region

isotropic power of GRB

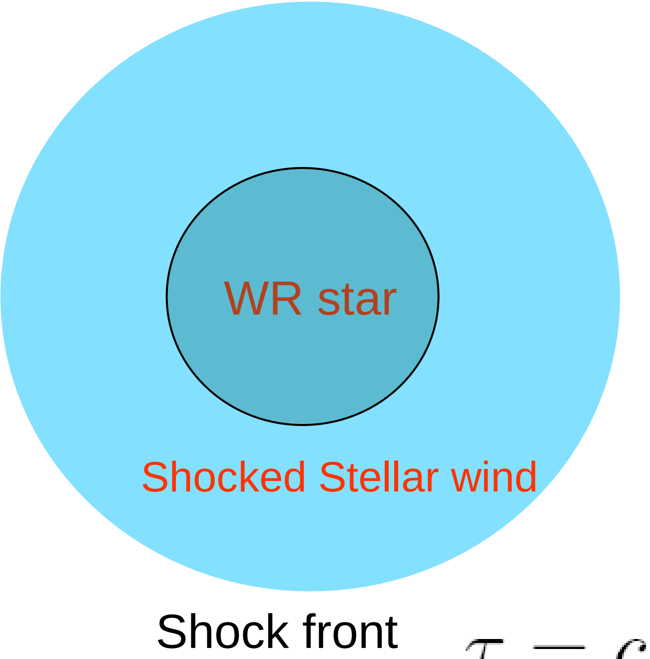
$$R_{shell} \approx \left(\frac{E_{iso}}{aT^4}\right)^{\frac{1}{3}} \approx 5\times10^{12}\,\mathrm{cm}$$

thermal temperature

radiation density constant

- BUT lack of Hydrogen lines implies a more compact star: larger radius explained by ***massive stellar wind***.

Campana et al. 2006



$$\tau = c/v_s$$

2) Shock velocity: V_s~c

$$\dot{M} \sim \frac{M_{shell} V_{wind}}{R_{shell}} \sim 3 \times 10^{-4}\ \mathrm{M_{\odot} yr^{-1}}$$

$$aT_{BB}^4 \sim 3 \rho_{wind} v_{shock}^2$$

ρ_{wind} is ~10^{12} g cm^{-3} and thus $v_{shock} \approx c$

A mildly-relativistic shock

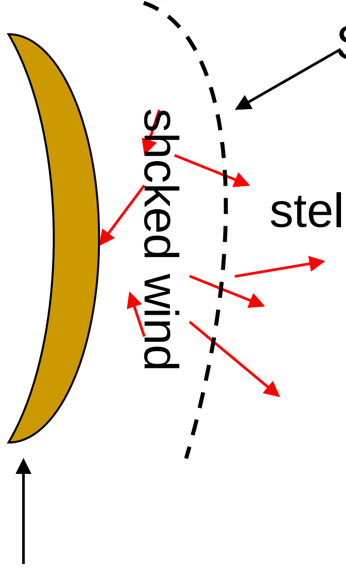
Common thermal and non-thermal emission origin of GRB060218/SN2006aj

- If there is a mildly relativistic ejecta, non-thermal emission may arise naturally (Wang, Li, Waxman & Meszaros 2007)

Bulk-motion Comptonization of thermal x-ray photons --- multiple scattering

Wang, Li, Waxman & Meszaros 2007

- An non-negligible optical depth ahead of the shock $\tau = c/v_s$
- Some thermal photons are repeatedly scattered by the electrons to increasingly higher energy before they can escape
- “photon acceleration”, giving rise to a nonthermal component



$\tau = c/v_s$~1

Shock front

shocked wind

stellar wind

Mildly relativistic ejecta from SN

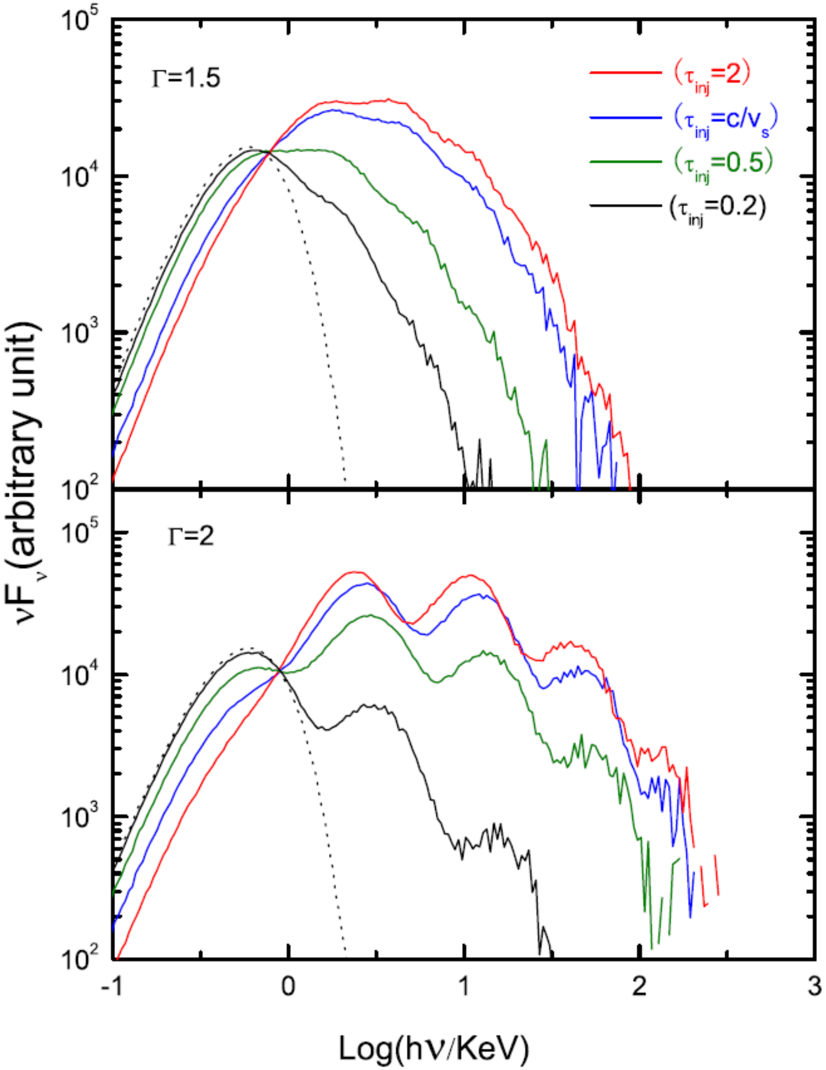
$\Gamma\beta \sim 1-2$

similar to “Fermi acceleration”

Simulation results --- time-integrated spectrum

- 10^6 thermal “seed” photons with kT=0.15KeV (black dotted line)
- Non-thermal component is indeed dominated for mildly relativistic shock
- Large Gamma, large peak energy, peak energy could be around a few KeV--- X-ray flash
- Spectrum becomes steeper at higher energies (decreasing tau effect)

$$\alpha = -\ln\tau/\ln A$$



wind parameters are: $\dot{M} = 10^{-4} M_\odot \mathrm{yr}^{-1}$ and $v_w = 10^8 \mathrm{cms}^{-1}$

Origin of mildly-relativistic jets

- Not fully known yet

Speculation: (Wang et al. 2007)

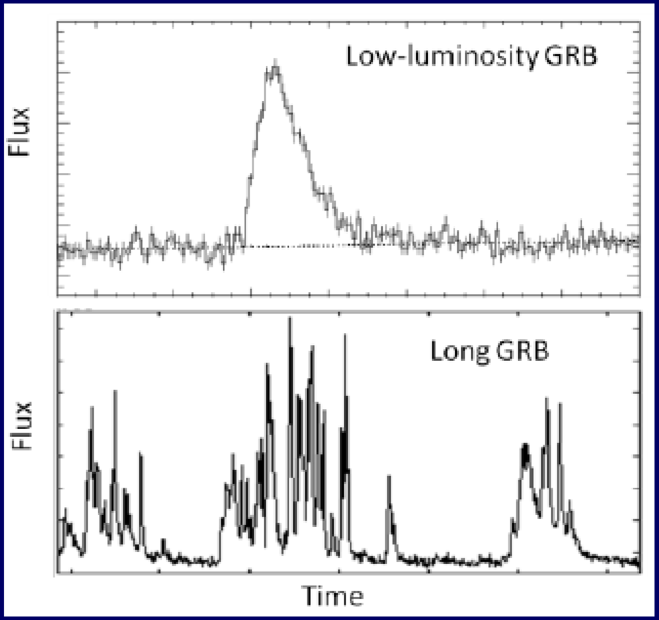
1. When the SN shock gets to the outer parts of the star, the shock accelerates in the density gradient of the envelope

Only ~10^49-10^50 erg needs to be in the mildly relativistic ejecta of GRB980425 and GRB060218

2**. the relativistic GRB jet is chocked and tunes into an isotropic mildly-relativistic ejecta**

Low-luminosity GRBs

- ~10^{-4} lower luminosity, <10^{48} erg/s
- Smooth light curve
- Soft spectrum
- Much more frequent



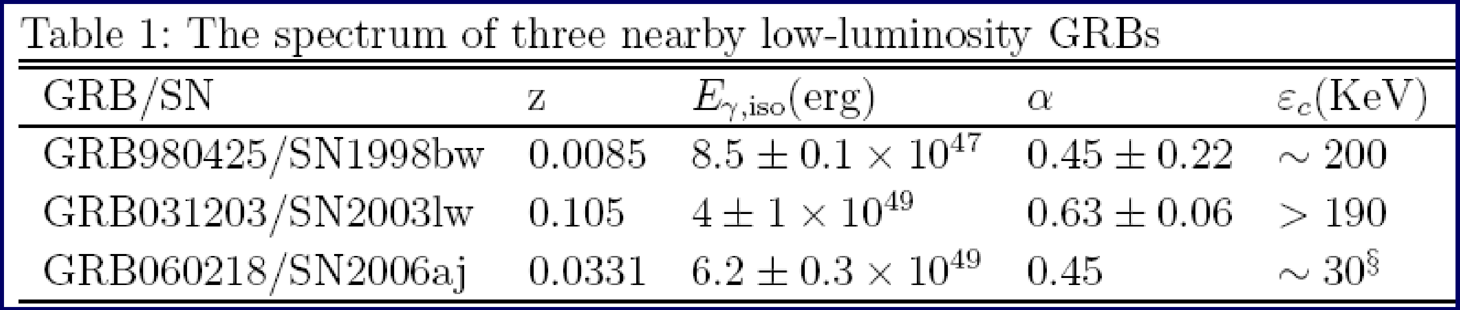
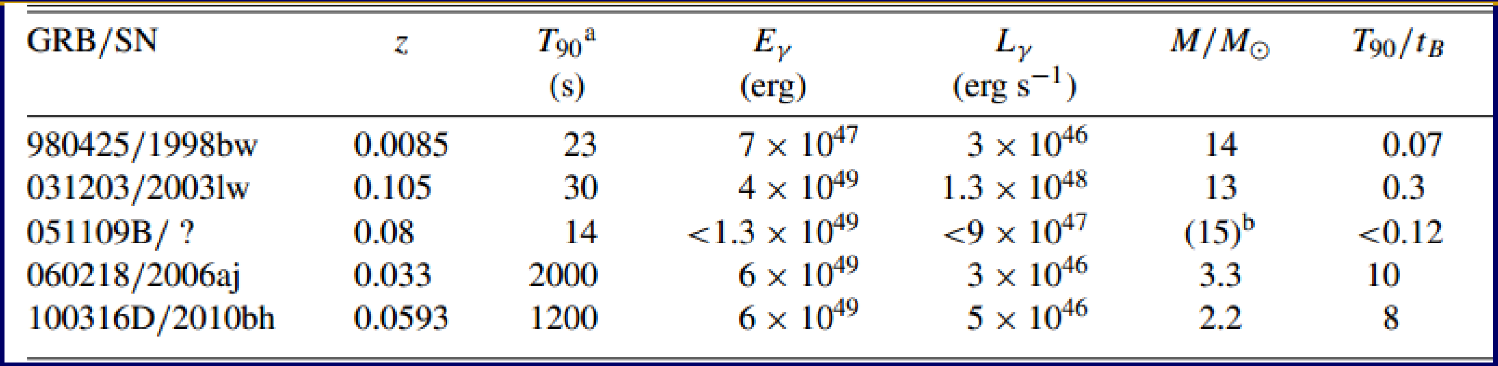


Table 1: The spectrum of three nearby low-luminosity GRBs

GRB/SN	z	$E_{\gamma,\mathrm{iso}}(\mathrm{erg})$	α	$\varepsilon_c(\mathrm{KeV})$
GRB980425/SN1998bw	0.0085	$8.5 \pm 0.1 \times 10^{47}$	0.45 ± 0.22	~ 200
GRB031203/SN2003lw	0.105	$4 \pm 1 \times 10^{49}$	0.63 ± 0.06	> 190
GRB060218/SN2006aj	0.0331	$6.2 \pm 0.3 \times 10^{49}$	0.45	$\sim 30^{\S}$

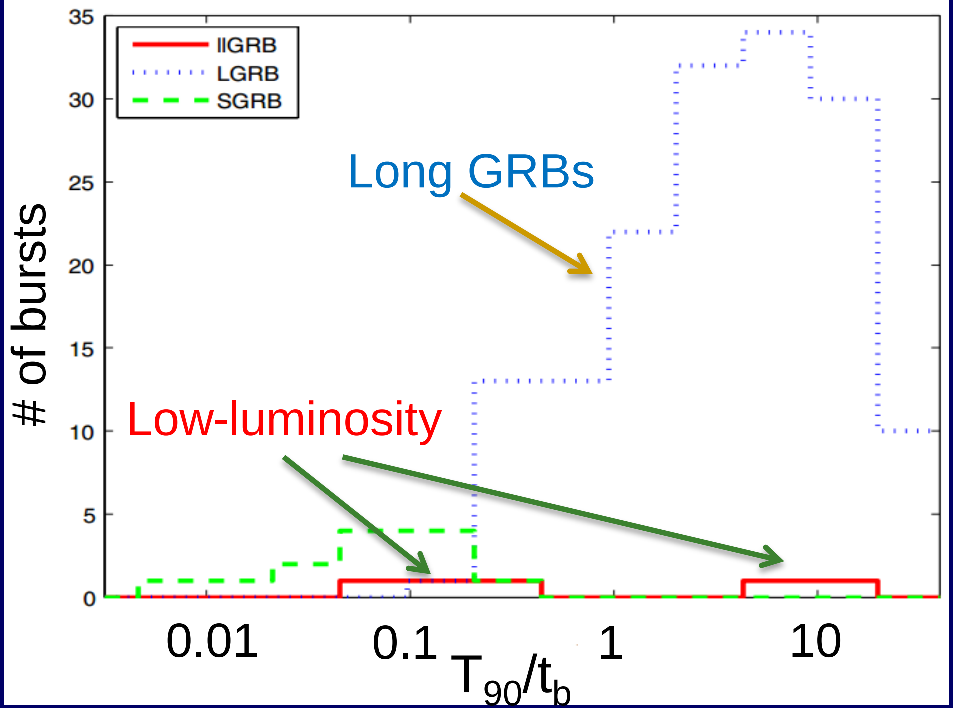
GRB100316D/SN2010bh

- Low-luminosity GRB is NOT a regular GRB with low luminosity



GRB/SN	z	T_{90}[a] (s)	E_γ (erg)	L_γ (erg s^{-1})	$M/M_\odot$	T_{90}/t_B
980425/1998bw	0.0085	23	7×10^{47}	3×10^{46}	14	0.07
031203/2003lw	0.105	30	4×10^{49}	1.3×10^{48}	13	0.3
051109B/ ?	0.08	14	$<1.3 \times 10^{49}$	$<9 \times 10^{47}$	(15)[b]	<0.12
060218/2006aj	0.033	2000	6×10^{49}	3×10^{46}	3.3	10
100316D/2010bh	0.0593	1200	6×10^{49}	5×10^{46}	2.2	8

Bromberg, Nakar & Piran 2012:



Low-luminosity GRBs are most likely (2σ) not produced by jets that successfully punches through their progenitor envelope

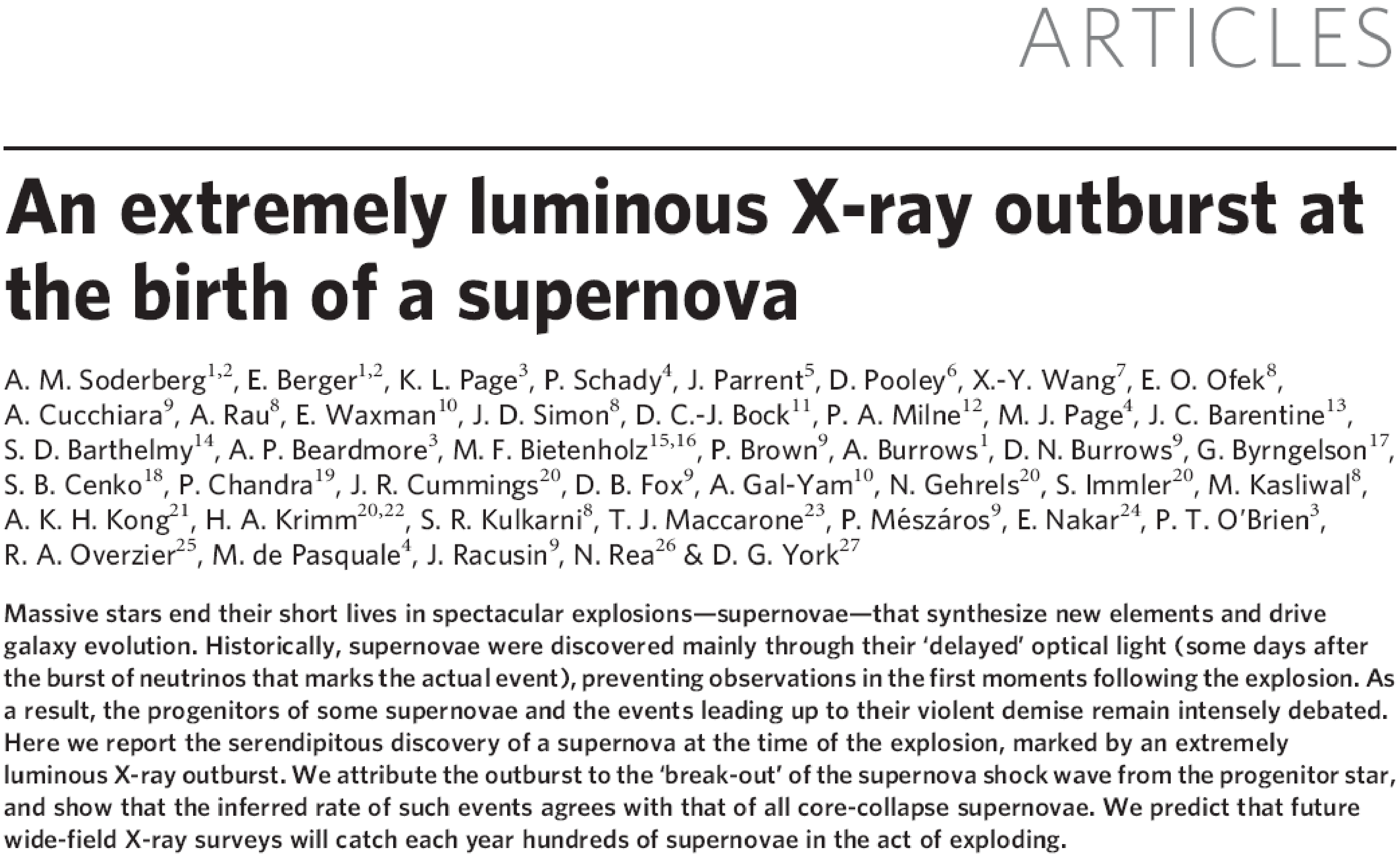
not successful jets

Even “failed” jets drive shocks that breakout of the stellar surface!

“failed” jets are much more frequent than successful ones

Morsony et al., 07

X-ray outburst 080109 associated with SN2008D



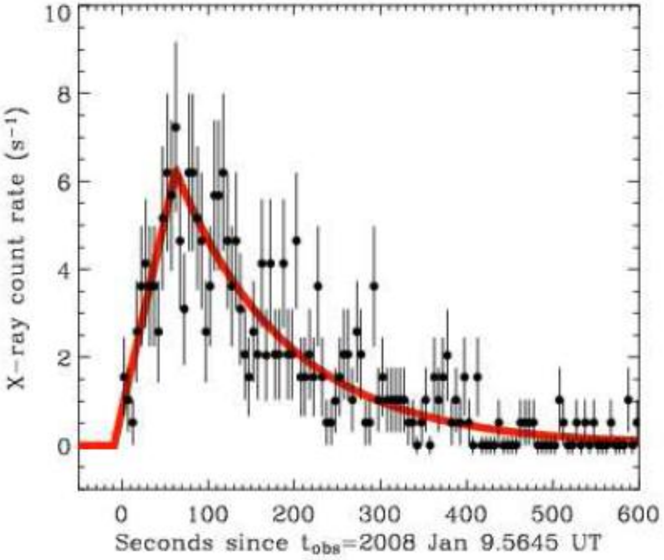
ARTICLES

An extremely luminous X-ray outburst at the birth of a supernova

A. M. Soderberg[1,2], E. Berger[1,2], K. L. Page[3], P. Schady[4], J. Parrent[5], D. Pooley[6], X.-Y. Wang[7], E. O. Ofek[8], A. Cucchiara[9], A. Rau[8], E. Waxman[10], J. D. Simon[8], D. C.-J. Bock[11], P. A. Milne[12], M. J. Page[4], J. C. Barentine[13], S. D. Barthelmy[14], A. P. Beardmore[3], M. F. Bietenholz[15,16], P. Brown[9], A. Burrows[1], D. N. Burrows[9], G. Byrngelson[17], S. B. Cenko[18], P. Chandra[19], J. R. Cummings[20], D. B. Fox[9], A. Gal-Yam[10], N. Gehrels[20], S. Immler[20], M. Kasliwal[8], A. K. H. Kong[21], H. A. Krimm[20,22], S. R. Kulkarni[8], T. J. Maccarone[23], P. Mészáros[9], E. Nakar[24], P. T. O'Brien[3], R. A. Overzier[25], M. de Pasquale[4], J. Racusin[9], N. Rea[26] & D. G. York[27]

Massive stars end their short lives in spectacular explosions—supernovae—that synthesize new elements and drive galaxy evolution. Historically, supernovae were discovered mainly through their 'delayed' optical light (some days after the burst of neutrinos that marks the actual event), preventing observations in the first moments following the explosion. As a result, the progenitors of some supernovae and the events leading up to their violent demise remain intensely debated. Here we report the serendipitous discovery of a supernova at the time of the explosion, marked by an extremely luminous X-ray outburst. We attribute the outburst to the 'break-out' of the supernova shock wave from the progenitor star, and show that the inferred rate of such events agrees with that of all core-collapse supernovae. We predict that future wide-field X-ray surveys will catch each year hundreds of supernovae in the act of exploding.

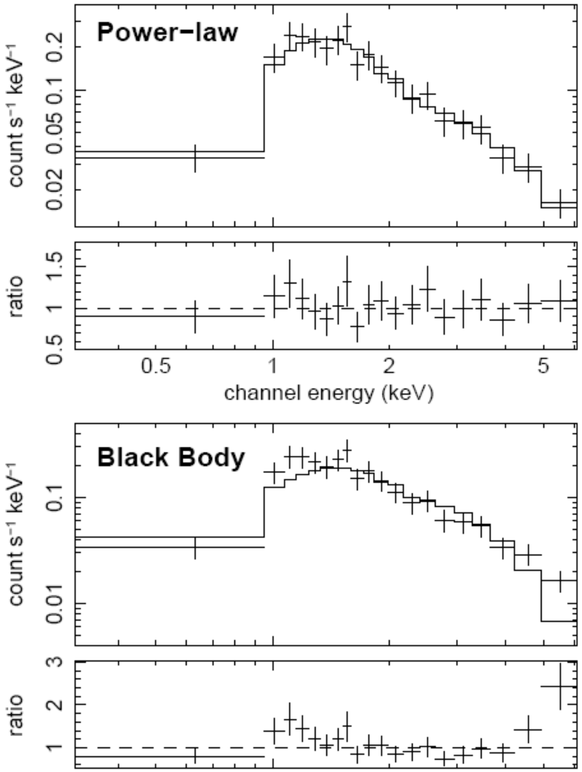
X-ray Outburst from A Normal SN

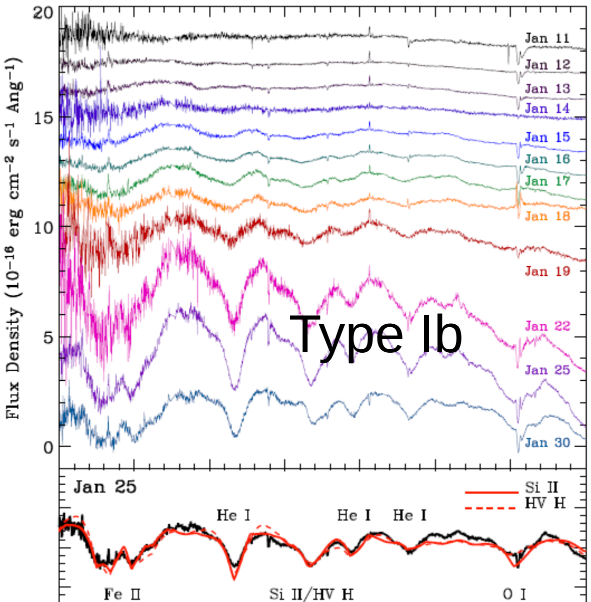


$E_X \approx 2 \times 10^{46}$ erg.

D=27 Mpc

Energetic: comparable to shock breakout Prediction (Matzner & Mckee 1999)





Type Ib

Shock breakout interpretation-shock breakout from a normal Ib star

- Thermal emission

Non-detection -> low temperature 3kT<=0.3KeV -> low shock velocity

$$\Gamma\beta = 1(\frac{T}{0.1KeV})^{4/3}(\frac{E_{th}}{4\times 10^{45}\mathrm{erg}})^{1/6}\gamma_d^{-4/3}$$

$$R_{ph} = 0.5\times 10^{12}(\frac{T}{0.1KeV})^{-4/3}(\frac{E_{th}}{4\times 10^{45}\mathrm{erg}})^{1/3}\gamma_d^{4/3}\mathrm{cm}$$

- Non-thermal emission

Bulk Comptonization emission

(Wang, Li, Waxman & Meszaros 2007)

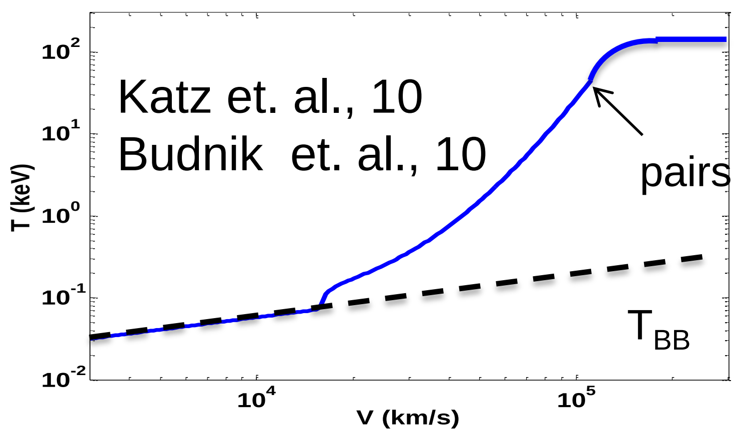
Trans-relativistic shock velocity for type Ib/c –quite reasonable

Relativistic shock breakout

Katz et. al., 10
Budnik et. al., 10
Nakar & sari

Main physical properties:

- the shock transition region is not in thermal equilibrium



- Constant post shock rest frame temperature ~100-200 keV

Difference between GRB060218/SN2006aj and XRO080109/SN2008D

- Engine exist or not ?
- Ordinary GRBs: strong engine, relativistic jets
- GRB060218/SN2006aj: a weak engine, maybe choked jet
- XRO080109/SN2008D: ordinary SN, may be no engine

EP 科学问题和探测率

- 检验超新星爆发基本图像
- 限制超新星前身星参数
- 揭示低光度伽玛暴的本质

- XRO080109/SN2008D 距离 27Mpc (Swift XRT)– EP 探测距离？
- Ib/c SN爆发率与II-p SN爆发率接近
- Ib/c SN shock-breakout爆发率与II SN爆发率接近

- 低光度暴--探测距离更远