The SN – GRB - NS Connection

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An explosive ancestry… leading to varying degrees of degeneracy:

SN – GRB – NS

- Gamma Ray Bursts (GRB) ← Black hole (BH) ← Supernova (SN) ← collapsar, …
- Magnetars, pulsars (neutron stars: NS), white dwarfs (WD)
- And what they lead to…:
  - → Ultra-high energy γ-ray, neutrinos (UHE γ, UHE ν)
  - → Ultra-high energy cosmic rays (UHECR) (GZK),
  - → Gravitational Waves (GW) (KHz, mHz, μHz…)
  - → Electromagnetic (EM) flares: γ, X, UV/O, sub-mm, R
Subramanian Chandrasekhar

- Explained WD as compact cores supported by degeneracy pressure of electrons
- Leading the way to later understanding of NS as more massive cores supported by deg.press. of neutrons;
- and understanding of BH, for even larger masses
GRB Sky & Temporal Distrib.

- Cosmological (isotropic) distribut.
- Out to $z \approx 4.5$ (20?)
- $\sim 1/\text{day} \ @ \ z \approx \text{few}$
- $\sim 1/3$ “short” (<2s) → NS mergers/mag?
- $\sim 2/3$ “long” (>2s) → massive coll/SN?
GeV $\gamma$ emission from GRB, PSR, SNR, other galactic, extragalactic & un-id sources

- GeV: space obs. (SAS-2, HEAO-A4, Kvant....)
- EGRET spark chamber: 5 GRB, 6 PSR & 60 blazars @ $\lesssim 10$GeV
- $+$ ~25 other Unidentified EGRET $\gamma$-ray sources
Common physical classification:

- **Thermonuclear** runaway explosion, on accreting WD; progenitor: $M_m \lesssim 10 M_\odot$
  \[\rightarrow\text{ Type Ia}\]

- **Core collapse** to NS (or BH) +envelope ejection; progenitor: $M_m \gtrsim 10 M_\odot$
  \[\rightarrow\text{ Type II}\]
  Type Ib, Ic
Thermonuclear runaway:

Type Ia, accretion onto a white dwarf.

Core collapse of a massive star;

(Cardall '03)
Core collapse SN

Cardall 03 & U.Tenn

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Core-collapse SN bounce, shock & thermal $\nu$ (10-30 MeV) production

( Cardall 03 & Terascale Supernova Initiative)
SN spectral class:

- **Type I**: absence of H features
  - Ia: strong Si feature
  - Ib: no/weak Si, strong He
  - Ic: no/weak Si, no/weak He
- **Type II**: obvious H features
  - IIp: \( \approx 2M\odot \) H-env, H-abs. features
  - IIL: \( \approx 2M\odot \) H-env, weak H-abs.feat
  - IIn: no/weak H abs, narrow H emiss

SN photometric class:

- **Type Ia**: opt. brightest at max. light, and: **good standard candles**!
  - supernova project: cosmology, accel. U, dark energy... SNAP, etc
- **Type Ib, Ic, II** (i.e. core collapse SNe): not very good standard candles...
  - but: very interesting ..! \( \Rightarrow \) NS, BH.. and **GRB**!
- Non-rotating single ms ★
- Mass-loss simplified
- Metallicity dependence?
- Core rotation, binary evol’n?
- etc

(from Heger, et al 03)
Remnant Type vs. Init. Mass & Z

At higher mass,
high metallic \( \Rightarrow \)
high wind mass loss \( \propto Z^{1/2} \);
stronger after H-env. is lost
\( \Rightarrow \) He core incr. smaller
\( \Rightarrow \) Remnant incr. less massive

At low metallic.
Mass loss Unimportant,
BH boundary det. by initial
Stellar mass
Remn. Type & envelope (or lack)  \Rightarrow SN type vs. Init. Mass & Z
Core rot. \( \Rightarrow \) Collapsar/Jet SN types

- Presence of JET \( \Rightarrow \) collapsar or anisotrop. SN:
  - Occurs if can assume large core rotation, e.g. from magn instab in single \( * \), or binary evol, etc
  - Anisotr. SN: obs.
  - Evidence from opt pol (few %) (both SN & GRB)
  - May help also understand anomalies in nucleosy, etc

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"Hypernova" \implies \text{Anisotropic SN} I b/c?

- Nomoto, Woosley, Fryer, Heger et al.: degree of anisotropy (and He core mass) may influence ejected $^{56}\text{Ni}$ mass (hence strength of optical display)
- Viewing angle influence observed velocity of ejection (and inferred $E_{\text{iso}}$)

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Remnant type vs. redshift
(tentative)

- Fraction of massive stars leading to various SN and compact remnant types follows from given Z-z dep.
- Implications: at high z, incr. potential for
  - UV/X/γ ionizing flux
  - CRs, ν’s, GW
  - seed accr BH (→AGNs)
  - GRB, XR/IR transients

Heger, Fryer et al, astroph/0212469
NS remnant ⇒ various outcomes:

- **“Normal”** B ($\lesssim 10^{13}$ G):
  - Young gamma/radio PSR
  - ms recycled PSR
  - Isolated neutron stars (XR,..)
  - Accreting X-ray pulsar
- **“Higher”** B ($\gtrsim 10^{13}$ G)
  - “Anomalous” X-ray pulsar/AXP
  - Magnetar: SGR (… GRB ?)
  ⇒ various interesting effects?
    - vacuum polariz.,
    - photon splitting…
• **Isolated pulsars:** \( \sim 1300 \) known

• Binary radio PSRs: (many in GCs,..); of particular interest for Gen.Relat., GW, mass det., etc

• **XR surface** emission: thermal spectrum – of interest for radius determination; not uniform (some pulsation); also a non-thermal PL component, ascribed to magnetospheric emission (more pulsed than thermal); extends down to O/IR

• **Binary XRP:** \( \sim 100 \), dozens w. cyclotron lines (e.g. XTE); of interest for field measurement. But: bright, \( \rightarrow \) not best Chandra, XMM targets; recent advances have been in faint objects

• XMM: detected in binary XRPs XR lines at low energies, ascribed to metals in acc.disk
PSR

- Radio to gamma emission:
- polar or outer gaps?
  ⇒ **GLAST** should tell
Cyclotron lines: XTE
(Coburn et al, 02, ApJ 580, 394);
Inferred B compatible with
spin up/down obs & young/
middle aged PSR surface
fields .. (but..)
Isolated X-ray PSRs

- **1E1207**: XR lines lines at 0.7, 1.4, 2.1 (coinc. w.instr line), maybe 2.8 keV → ?
- Bignami et al: cyclotron harmonics, indicate lower than usual field?
- Pavlov et al: single PSR, low surf temp and field, so oscill. strenght of higher harm too low to explain harmonics. Could be He in strong field ?(magn. levels quite ≠ unmagn.)
- Several middle aged (10Kyr-Myr) isolated PSR show such lines;
PSR Nebulae & MHD winds

• PSR winds: seen by Chandra in \( \gtrsim 20 \) PSR nebulae (\( \gtrsim 30 \) at other wavelenghts)

• Crab wind: outer wisps move (also opt)

• \( \leftarrow \) Vela PSR: Chandra measures jet motion, especially interesting faint “outer jet”

SGR/MGR sim.
(courtesy NASA)

- **SGRs**: leading explanation is **MGR** (NS w. $B \gtrsim 10^{13}$ G)
- **AXP**: probably not powered by accretion: No companion seen, and O/IR spectrum does not fit disk
  \[ \rightarrow \text{may be that } \text{AXP} \sim \text{MGR} \? \]
  (but: no compelling MGR explanation for O/IR sp)
- Also, two AXPs have now been seen to burst
- SGR X-ray sp. in quiesc is same as AXP, $\Rightarrow$ AXP $\leftrightarrow$ SGR
- March 5 SGR: used to have harder quiesc sp than AXPs, recently softened, looks $\sim$ AXP
QED effects on XR polarization modes

Even for $B \sim 10^{12}$ G, but particularly for $B \gg B_Q = m^2 c^3 / \hbar e = 4.413 \times 10^{13}$ G, at a critical freq ($\chi / \gamma$) where vacuum effects cancel plasma effects → the polariz normal modes, as they go through the critical region, retain the same handedness, but change from para to perp (E resp B) ; in old plasma lit. the mode “does not change”, in some new lit. it “does change” identity.

(Ozel, Lai,….Pavlov, Meszaros..):
GRB: → Hyperaccreting Black Holes (current paradigm)

Short
$(t_\gamma \lesssim 2 \text{ s})$

Long
$(t_\gamma \gtrsim 2 \text{ s})$

NS - NS merger

BH - NS merger

very, very fast jet

0.01 $M_\odot$
torus

0.1$M_\odot$
torus

BH - WD merger

1$M_\odot$
torus

few $M_\odot$
torus

NS/BH - He core merger after common envelope

collapsar = rotating, collapsing "failed" supernova

“long” **GRB** from “collapsars”

A diagram illustrates the processes leading to a GRB. It shows a 30 solar-mass star and a Wolf-Rayet star, each with a core and hydrogen envelope. The stellar wind carries off the outer envelope, leaving behind a core of heavier elements. Iron can’t generate energy by fusion, so when the core can no longer support the star’s weight, it collapses into a black hole. A disk of matter feeds jets of high-speed particles along the star’s poles.
Collapsar GRB (cont.)

The jets quickly tunnel to the star’s surface.

The jets and wind from the accretion disk blow the star apart.

The gamma rays we see in a burst are actually produced when relativistic particles run into each other about 10^{14} cm away from the star.

Like a snow shovel, the jets...
**GRB: basic numbers**

- **Distance**: $0.1 \approx z \approx 4.5 \rightarrow D \sim 10^{28} \text{ cm}$
- **Fluence**: $F = \int \text{flux}.\text{dt} \sim 10^{-4} - 10^{-7} \text{ erg/cm}^2$
  
  $\sim 1 \text{ ph/cm}^2$
- **Energy output**: $10^{53} (\Omega/4\pi) D_{28.5}^2 F^{-5} \text{ erg}$

  jet: $\Omega \sim 10^{-2} - 10^{-1} \rightarrow E_{\gamma,\text{tot}} \sim 10^{51} \text{ erg}$

  $E_{\gamma,\text{tot}} \sim L_\Theta \times 10^{10} \text{ year} \sim L_{\text{gal}} \times 1 \text{ year}$

- **Rate (GRB)**: $\sim 1/\text{day} \rightarrow 10^{-6} (\Omega/2\pi)^{-1} \text{ /yr/gal}$

  (whereas $\text{Rate [SN]} \sim 10^7 \text{ /yr} \sim 1/\text{s at } z \approx 1$)
BH + accr. Torus $\rightarrow$ Jet

- Both collapsar or merger $\rightarrow$ BH+accr.torus$\rightarrow$fireball
- Massive rot. $\star$: sideways pressure confines/channel outflow $\rightarrow$ fireball Jet
- Nuclear density hot torus $\rightarrow$ can have $\nu\nu\rightarrow e^\pm$ jet
- Hot infall $\rightarrow$ convective dynamo $\rightarrow$ $B\sim10^{15}$ G, twisted (thread BH?) $\rightarrow$ Alfvénic or $e^\pm\gamma$ jet
- (Note: magnetar might do similar)
Explosion  →  FIREBALL

- $E_\gamma \gtrsim 10^{51} \Omega_{-2} D_{28.5}^2 F_{-5}$ erg
- $R_0 \sim c t_0 \sim 10^7 t_{-3}$ cm
  - Huge energy in very small volume
- $\tau_{\gamma\gamma} \sim (E_\gamma/R_0^3 m_e c^2) \sigma_T R_0 >> 1$
  - Fireball: $e^\pm, \gamma, p$ relativistic gas
- $L_\gamma \sim E_\gamma / t_0 >> L_{\text{Edd}}$ → expanding ($v \sim c$) fireball
  (Cavallo & Rees, 1978 MN 183:359)
- Observe $E_\gamma > 10$ GeV …but
  $\gamma\gamma \rightarrow e^\pm$, degrade $10$ GeV → $0.5$ MeV?
  $E_\gamma E_t > 2 (m_e c^2)^2 / (1 - \cos \Theta) \sim 4 (m_e c^2)^2 / \Theta^2$
  - Ultrarelativistic flow → $\Gamma \gtrsim \Theta^{-1} \sim 10^2$
  (Fenimore et al. 93; Baring & Harding 94)
Jet (outside the star) → shocks

- **Shocks** expected in any unsteady supersonic outflow (esp. in a non-vacuum environment)
- **Internal** shocks: fast shells catch up slower shells (unsteady flow)
- **External** Shock: flow slows down as it plows into external medium

- **NOTE:** “external” and “internal” shocks might be expected also while jet is **inside** star, as well as after it is **outside** the star.

  If inside: $\gamma$s do **not** escape (but $\nu$ can)
  If outside: $\gamma$s **do** escape (and $\nu$ too)
Non-thermal $\gamma$s: Internal & External Shocks

in optically thin medium outside progenitor:

$\implies$ SHORT & LONG-TERM BEHAVIOR

Shocks solve radiative inefficiency problem (reconvert bulk kin. en. into random en. $\rightarrow$ radiation)

$\Gamma$

$\Gamma$ first grows $\propto r$, then coasts $\propto$ constant, until …

Outside the star, after jet is opt. thin:

Internal shocks: $r_i \sim 10^{12}$ cm

$\rightarrow$ $\gamma$-rays (burst, $t \sim$ sec)

Externals shocks start at $r_e \sim 10^{16}$ cm, progressively weaken as it decelerates

PREDICTION:

- External forward shock spectrum softens in time:
  X-ray, optical, radio …
  $\rightarrow$ long fading afterglow!
  ($t \sim$ min, hr, day, month)

- External reverse shock (less relativistic):
  Optical $\rightarrow$ quick fading ($t \sim$ mins)
External **Forward & Reverse Shock**

**Synchroton & IC spectrum**


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GRB 970228: BeppoSAX
Discovery of an afterglow

- X-ray location: 2-3 arcmin → raster
- → optical (arcsec) & radio location
- Can identify host galaxy, redshift
- Located at cosmological dist.

Feb 28
March 3

F_x \sim 3 \times 10^{-12} \text{ erg cm}^{-2} \text{ keV s}^{-1}, \text{ decr. By 1/20}

(Costa et al 1997, Nature 387:783)
GRB afterglow blast wave model

- Simplest case: adiabatic forward shock synchrotron rad’n from shock-accel. non-thermal e-
  - $F(\nu, t) \propto \nu^{-\beta} t^{-\alpha}$
  - $\alpha = (3/2) \beta$
  - Parameters $E_0$, $\epsilon_e$, $\epsilon_B$, ($\beta=(p-1)/2$)

GRB 970228 as blast wave:

Wijers, Rees & Meszaros 97 MNRAS 288:L51 fit to
Snapshot Afterglow Fits

- Simplest case: 
  $t_{\text{cool}}(\gamma_m) > t_{\text{exp}}$, where 
  $N(\gamma) \propto \gamma^p$ for $\gamma > \gamma_m$ (i.e. 
  $\gamma_{c(ool)} > \gamma_m$)

- 3 breaks: $\nu_{a(bs)}$, $\nu_m$, $\nu_c$

- $F_\nu \propto \nu^2 \left(\nu^{5/2}\right)$; $\nu < \nu_a$
  $\propto \nu^{1/3}$; $\nu_a < \nu < \nu_m$
  $\propto \nu^{-(p-1)/2}$; $\nu_m < \nu < \nu_c$
  $\propto \nu^{-p/2}$; $\nu > \nu_c$


Break frequency decreases in time (at rate dep. on whether ext medium homog. or wind (e.g. $\rho \propto r^{-2}$))

(Mészáros, Rees & Wijers '98 ApJ499:301)
Scintillation & Afterglow Limb Brightening

- Radio scintillations:
  \[ \Delta r \approx 10^{16} \text{ cm} \] at distance \( r \approx 10^{17} \text{ cm} \)
- But: equal-arrival time surfaces are “pears”, edges “younger/bright”
  \[ \text{→ limb-brightening, obs. size } < \text{ distance} \]

(Waxman 98; Sari 98; Panaitescu-Meszaros 98)

(Granot et al, 99)
GRB Afterglow Radio Detections

Waxman, Kulkarni, Frail 99: Scintillations $\rightarrow$ (small) size!

Frail, Kulkarni et al 01
fireball model & calorimetry
Shock Photon Spectrum

- **Non-thermal power law** spectrum, both in int. and ext. shocks, due to
- **Synchrotron**, peak at \(~200~\text{keV}~(\text{or}~\sim~\text{eV})\)
- **Inv. Compton**, peak \(\sim\text{GeV}~(\text{or}~\sim200~\text{keV})\)
- Sy peak location, ratio Sy/IC dep. on \(B_{\text{sh}}, \gamma_{e,m}\)
- Peak **softens** with time
- Ratio Sy/IC **decr** w. time

\[ E^2N_E \]

\[ F_E \]

\[ R \quad O \quad X, \gamma \]

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Fast Opt. Transients: ROTSE

- **Robotic Optical Transient Search Experiment**
  (Akerlof, et al, 99, Nat 398, 400)
- Cannon f/1.8 35mm cams coupled to CCD
- fast slew (3s anywhere)
- Detected bright, prompt (15s after trigger) optical flash in GRB990123
- Successor experiments: **ROTSE III, Super-LOTIS, RAPTOR, KAIT, TAROT, NEAT, Faulkes, REM**, etc.
Prompt Optical Flashes

- **GRB 990123** → bright (9th mag) prompt opt. transient (Akerlof et al. 99)
  - 1st 10 min: decay steeper than forw. shock
- Interpreted as reverse external shock (predicted: Meszaros & Rees '97)
- **99-02: Great Desert:**
  - Lack of flashes, upper limits $m_v \sim 12-15$
- **but:** New generation robotic tels:
  - ROTSE III, Super-LOTIS, RAPTOR, KAIT, TAROT, NEAT, Faulkes, REM; etc
- → **new** prompt optical flashes:
  - GRB 021004, 021211: similar to GRB 990123
- → **new** “semi- prompt” flashes,
  - (ROTSE IIIa (AU), ROTSE IIIb (TX)):
  - GRB 030418, 30723: ≠ from GRB 990123!
  - $t > 211, 50$ s resp, see forw. shock only?
  - steep rise (ascribed to dusty stell. wind)
  - $m_R \sim 17$ at $t \sim 30$ min, then PL -1.35 decay

(Rykoff et al. astro-ph/0310501)
Light curve break: Jet Edge Effects

- Monochromatic break in light curve time power law
- expect $\Gamma \propto t^{-3/8}$, as long as $\theta_{\text{light cone}} \sim \Gamma^{-1} < \theta_{\text{jet}}$, (spherical approx is valid)
- “see” jet edge at $\Gamma \sim \theta_{\text{jet}}^{-1}$
- Before edge, $F_\nu \propto (r/\Gamma)^2 \cdot l_\nu$
- After edge, $F_\nu \propto (r\theta_{\text{jet}})^2 \cdot l_\nu$ → $F_\nu$ steeper by $\Gamma^2 \propto t^{-3/4}$
- After edge, also side exp. → further steepen $F_\nu \propto t^{-p}$
Jet Collimation & Energetics

- Jet opening angle inv. corr. w. $L_\gamma$ (iso)
- $\rightarrow L_\gamma$(corr) $\sim$ const.
- GRB030329: evid. for 2-comp. jet: $\theta_\gamma \sim 5^\circ < \theta_{\text{radio}} \sim 17^\circ$
- $\Rightarrow E_{\text{total}} = E_\gamma + E_{\text{kin}}$ $\sim$ const.
  ($\rightarrow$ quasi-standard candle)
Collapsar & SN: does one imply the other?

- Core collapse of star w. $M \gtrsim 30 M_\odot$
  $\rightarrow$ BH + disk (if fast rot.core)
  $\rightarrow$ jet (MHD? baryonic? high $\Gamma$,
  + SNR envelope eject (?)
- 3D hydro simulations (Newtonian SR) show that baryonic jet w.
  high $\Gamma$ can be formed/escape
- SNR: not seen *numerically* yet
  (but: several previous observational suggestions, e.g. late l.c. hump + reddening- and debate);
  ....... and more recently ...
GRB 030329 ↔ SN 2003dh : Yes!

- Nearest “unequivocal” cosmological GRB: $z=0.17$
- GRB-SN association: “strong”
- Fluence: $10^{-4}$ erg cm$^{-2}$, among highest in BATSE, but $\Delta t \sim 30$ s, nearby;
  $E_{\gamma,iso} \sim 10^{50.5}$ erg: ~typical,
- $E_{SN2003dh,iso} \sim 10^{52.3}$ erg
  $\sim E_{SN1998bw,iso} (\leftrightarrow grb980425)$
  $v_{sn,ej} \sim 0.1c$ (→ “hypernova”)
- GRB-SN simultaneous? at most: $\lesssim 2$ days off-set (from opt. lightcurve)
  (→ i.e. not a “supra-nova”)
- But: might be 2-stage (<2 day delay) ★- NS-BH collapse ?
  $\rightarrow$ predictions may test this!
Other GRB-SN

- Earliest, most famous & debated example: (Galama et al, 1998) GRB980425-SN1998bw
  \( E_{\text{sn}} \sim 10^{52} \text{ erg}, \text{ but } z \sim 0.008, \ E_{\text{grb,iso}} 10^{47} \text{ erg odd} \)
- Other possible examples (w/o SN sp.): “red bump” in lightcurve:
  GRB980326 (Bloom 99), GRB970228 (Reichart 99, Galama 00), GRB000911 (Lazzati 01),
  GRB991208 (Castro 01), GRB990712 (Sahu 00), GRB011211 (Bloom 02), GRB020405 (Price 03)
- Red bump alternative model: dust sublimation or scattering?
  (Waxman-Draine 00, Esin-Blandford 00)
  Possible, but SN spectrum now available in at least two cases

Dela Valle et al, 2003
AA 406, L33
END
Fraction of massive stars leading to various SNe & GRB

Heger et al. 03