Gamma-Ray Bursts, Collapsars and Hypernovae

Cosmological gamma-ray bursts are some of the most energetic events in the Universe, some of which are known to be related to hypernovae, i.e., very energetic supernova-like events

Literature Review:

Gamma-Ray Bursts: Progress, Problems & Prospects, Zhang, B., & Mészáros, P., (astro-ph/0311321)

Hypernovae and other black-hole forming supernovae: ..., Nomoto et al. (astro-ph/0308136)

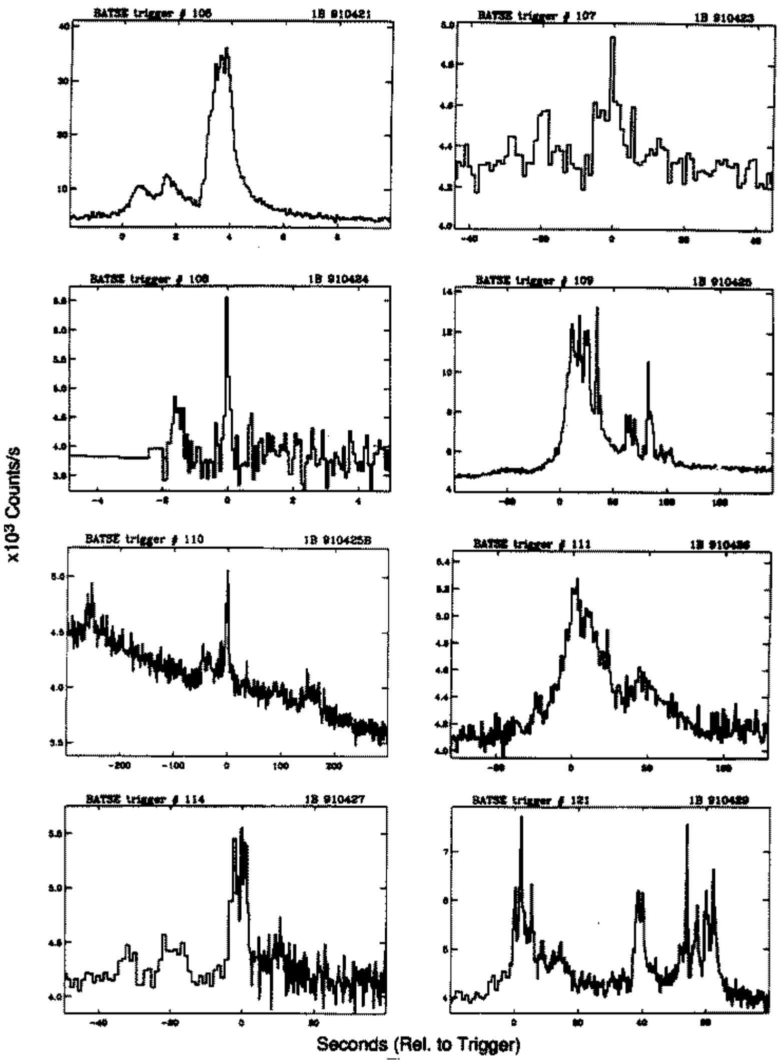
Gamma-Ray Bursts: The Central Engine, S. E. Woosley (astro-ph/9912484)

Collapsars, Gamma-Ray Bursts, and Supernovae, Woosley et al. (astro-ph/9909034)

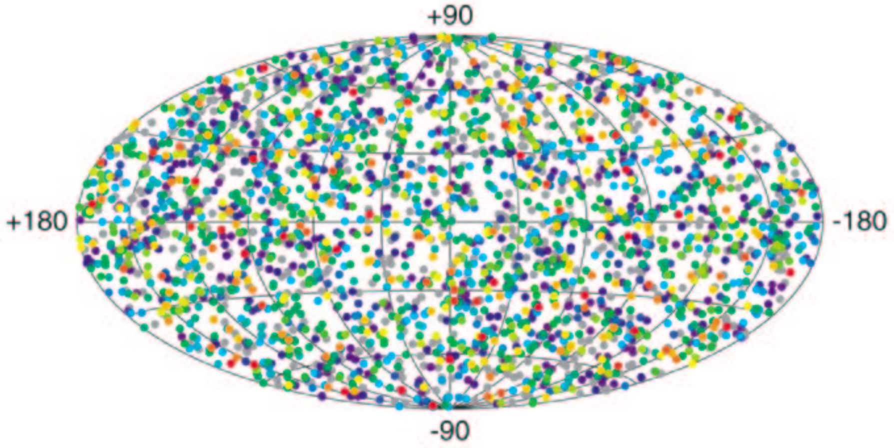
Supernovae, Jets, and Collapsars, MacFadyen, et al. (astro-ph/9910034)

Gamma-Ray Bursts (GRBs)

- discovered by U.S. spy satellites (1967; secret till 1973)
- have remained one of the biggest mysteries in astronomy until 1998 (isotropic sky distribution; location: solar system, Galactic halo, distant Universe?)
- discovery of afterglows in 1998 (X-ray, optical, etc.) with redshifted absorption lines has resolved the puzzle of the location of GRBs → GRBs are the some of the most energetic events in the Universe
- duration: 10^{-3} to $10^{3}\,$s (large variety of burst shapes)
- bimodal distribution of durations: $0.3\,$s (short-hard), $20\,$s (long-soft) (different classes/viewing angles?)
- GRBs are no standard candles! (isotropic) energies range from 5×10^{44} to $2 \times 10^{47}\,$J
- highly relativistic outflows (fireballs): ($\gamma \gtrsim 100$), possibly highly collimated/beamed
- GRBs are produced far from the source ($10^{11} - 10^{12}\,$m): interaction of outflow with surrounding medium (external or internal shocks) → fireball model
- relativistic energy $\sim 10^{46} - 10^{47}\,\mathrm{J}\,\epsilon^{-1}\,f_{\Omega}$ (ϵ: efficiency, f_{Ω}: beaming factor; typical energy $10^{45}\,$J?)
- event rate/Galaxy: $\sim 10^{-7}\,\mathrm{yr}^{-1}\,(3 \times 10^{45}\,\mathrm{J}/\epsilon\,E)$



2704 BATSE Gamma-Ray Bursts



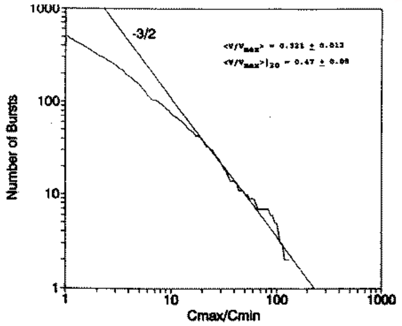


Figure 4. Intensity distribution for BATSE bursts. The measure of intensity is the maximum count rate divided by the threshold count rate.

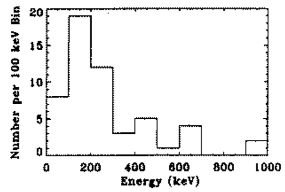


Figure 8. The distribution of the energy of the peak emission per 1 logarithmic energy interval.

Figure 7. The duration distribution for 222 BATSE bursts, as measured by T_{90}. The solid histogram represents the raw data; the dashed histogram represents the data convolved with measurement errors.

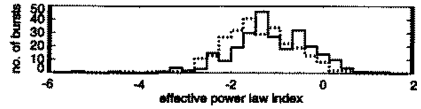


Figure 9. The distribution of burst spectral indices in the 50 to 300 keV ergy band. The solid line represents the distribution for the peak rate spectr and the dotted line represents the distribution for the total fluence spectrun

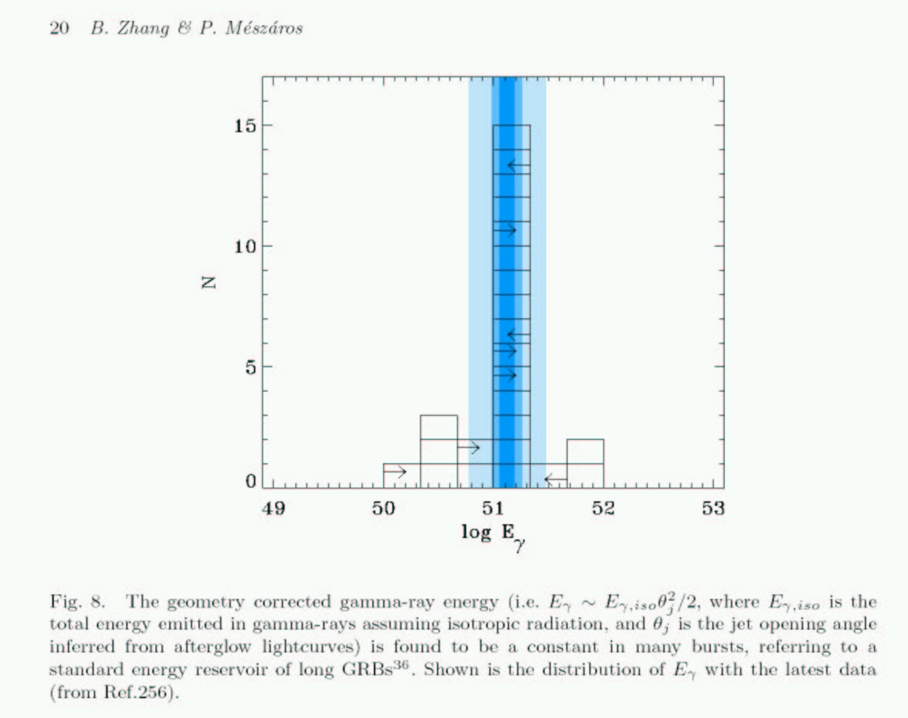
Meegan et.al. (1994)

Intrinsic Distribution of γ energies

- corrected for beaming

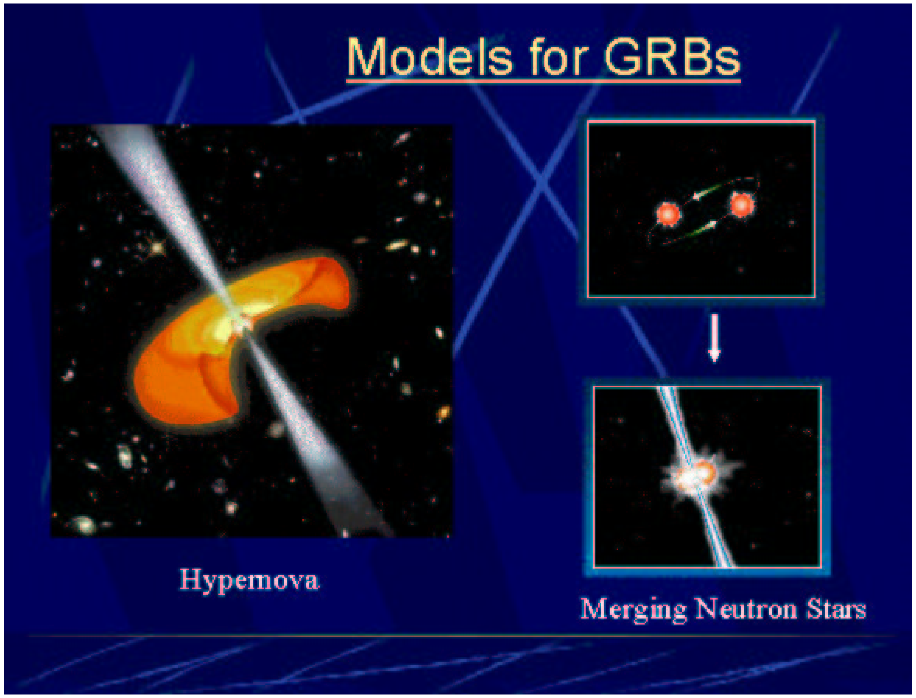
but: depends on beaming model: uniform beam or structured beam (i.e. where Lorentz factor *varies* with angle)

(10^7 ergs $\equiv 1$ J, $1\,M_\odot c^2 = 2 \times 10^{47}$ J)



20 *B. Zhang & P. Mészáros*

Fig. 8. The geometry corrected gamma-ray energy (i.e. $E_\gamma \sim E_{\gamma,iso}\theta_j^2/2$, where $E_{\gamma,iso}$ is the total energy emitted in gamma-rays assuming isotropic radiation, and θ_j is the jet opening angle inferred from afterglow lightcurves) is found to be a constant in many bursts, referring to a standard energy reservoir of long GRBs[36]. Shown is the distribution of E_γ with the latest data (from Ref.256).



Models for GRBs

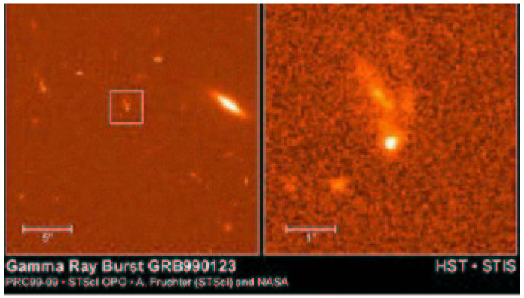
Hypernova

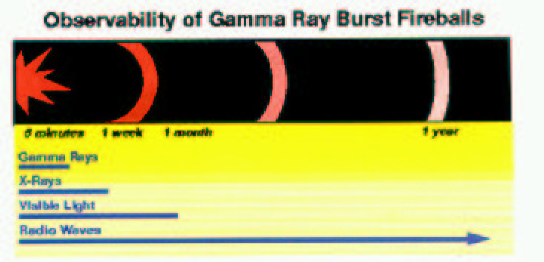
Merging Neutron Stars

Popular Models

- merging compact objects (two NS's, BH+NS) → can explain short-duration bursts (Note: observationally nothing is known about their location in galaxies)
- hypernova (very energetic supernova associated with formation of a rapidly rotating black hole)
  → jet penetrates stellar envelope → GRB along jet axis (large beaming)

Gamma−Ray Bursts: Afterglows





Properties to be explained:

- time variability: 10^{-3} s (emitting region $\sim 10^5$ m) → relativistic fireball
- Problem: most photons have energies > 0.5 MeV → optically thick to pair production $\gamma\gamma \rightarrow e^+ e^-$ → rapid photon downgrading of (to < 0.5 MeV) → conversion into kinetic energy → thermal spectrum
- need very clean environment (no pollution with baryon) → $e^\pm - \gamma$ fireball models
- need to reconvert kinetic energy into non-thermal emission (when fireball becomes optically thin)

Relativistic fireball models

- need high Lorentz factor Γ to
  - ▷ get relativistic beaming: $\theta_b \sim 1/\gamma$ ($\Omega \sim 1/\gamma^2$)
  - ▷ diminish pair production (relative angle at which photons collide decreases → increases pair production threshold)
  - ▷ best estimates: $\Gamma \sim 10^2$ (estimates have come down in recent years)
- problem: simple relativistic fireball model produces modified blackbody spectrum, efficiently converts energy into kinetic energy
- solution:
  - ▷ reconvert kinetic energy into random energy via shocks after the flow has become optically thin (mainly synchrotron radiation)
  - ▷ internal shocks in relativistic flow (faster portion of the flow catch up with slower portions)
  - → probably responsible for a lot of the fine structure in the bursts (but also from variability in central engine!)
  - ▷ external shock when the fireball runs into the external medium
  - → can produce multiple peaks, long smooth bursts
- fireball models can reproduce the main features of observed bursts, irrespective of the detailed physics of the central engine

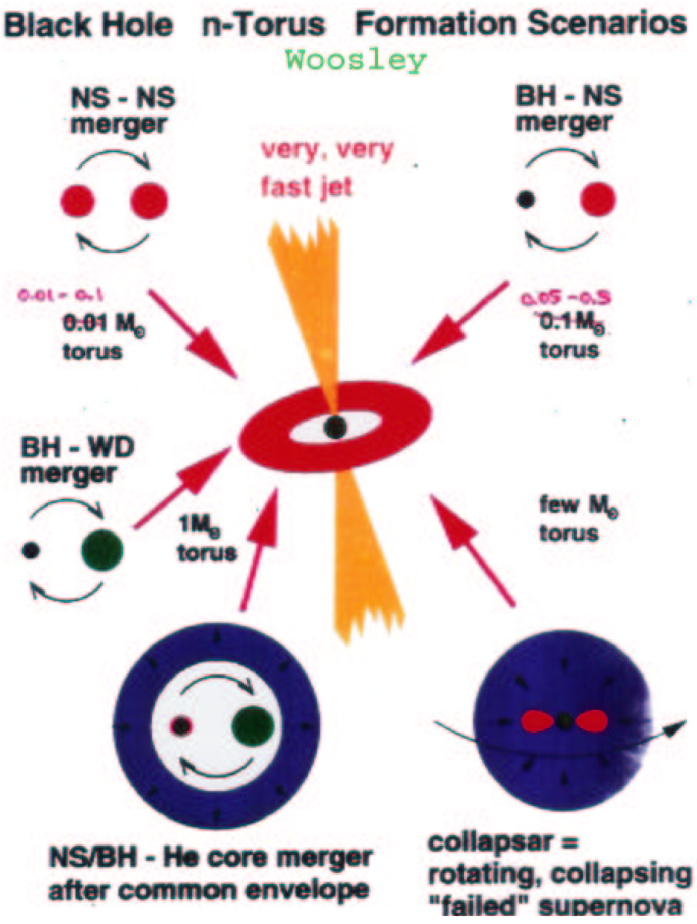
- Note: recent work has mainly concentrated on GBRs with afterglows; these are exclusively long-duration bursts → possibility that short-duration bursts are associated with compact mergers, long-duration bursts with hypernovae

Phases

- the central engine ($t \sim 10^{-3}\,s$)
- the burst phase ($t \sim 10^{-1} - 10^{2}\,s$)
- the afterglow ($t \sim 10\,s \to \infty$)

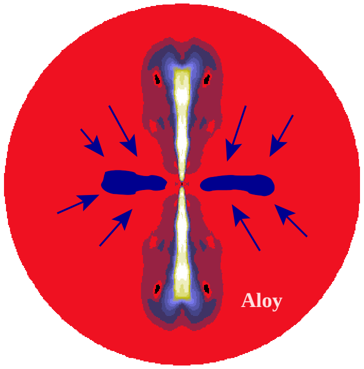
The central engine

- need to extract energy from collapse
  - ▷ rest-mass energy from disc: $42\,\%$ (max. rotating BH; $6\,\%$, non-rotating BH)
  - ▷ BH spin energy: up to $29\,\%$ (Blandford, Znajek mechanism: extraction of spin energy through threading the horizon of a spinning black hole surrounded by an accretion disc with magnetic fields)
- all models tend to have a disc (accretion torus): $M_d \sim 10^{-2} - 1\,M_\odot$
- maximum extractable energy
  - ▷ from torus: $1 - 10 \times 10^{46}\,J\,(M_d/M_\odot)$
  - ▷ from BZ mechanism: $5 \times 10^{46}\,J\,f(a)\,(M_{BH}/M_\odot)$ ($f(a) = 1 - ([q + \sqrt{1 - a^2}]/2)^{1/2} \leq 0.29$ a : angular momentum parameter)
- production of relativistic jet
  - ▷ $\nu\overline{\nu} \to e^+ e^-$ along rotation axis (low baryon loading); probably not efficient enough
  - ▷ more likely: MHD jet (Poynting jet)



Hypernovae, Collapsars and GRBs

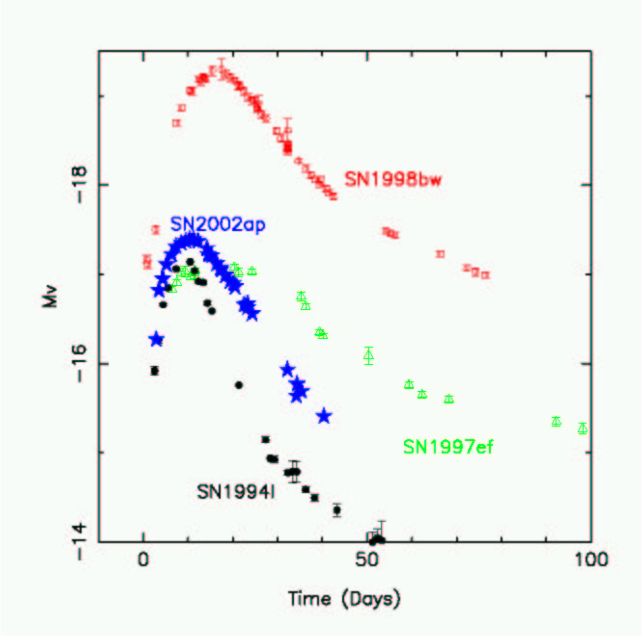
- a “new” explosion type?
- a more energetic supernova with a range of explosion energies: $5 - 50 \times 10^{44}\,\mathrm{J}$ (Mazzali, Nomoto, Maeda)
- classification criterion: few broad lines → high kinetic energy → high explosion energy
- asymmetric explosions?
- some are associated with long-duration gamma-ray bursts (GRBs, SN 98bw, SN 03dh)
- possibly associated with the formation of a black hole from a rapidly rotating compact core (Woosley)



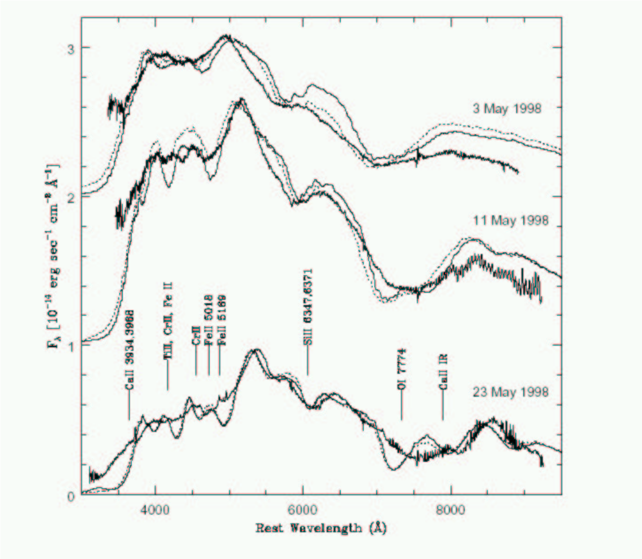
- ▷ two-step black-hole formation: neutron star, accretion from massive disc → black hole → relativistic jet → drills hole through remaining stellar envelope → escaping jet → GRB
- ▷ requires rapidly rotating helium (or CO) star

- presently all hypernovae have been classified as SNe Ic (i.e., no H, He), but only 1 in 100 Ib/Ic SNe are hypernovae (Podsiadlowski, Mazzali, Nomoto … 2004)
- HNe/GRBs are rare! ($10^{-5}\,\mathrm{yr}^{-1}$)
- Note: Hypernovae are efficient producers of Fe (just like SNe Ia)

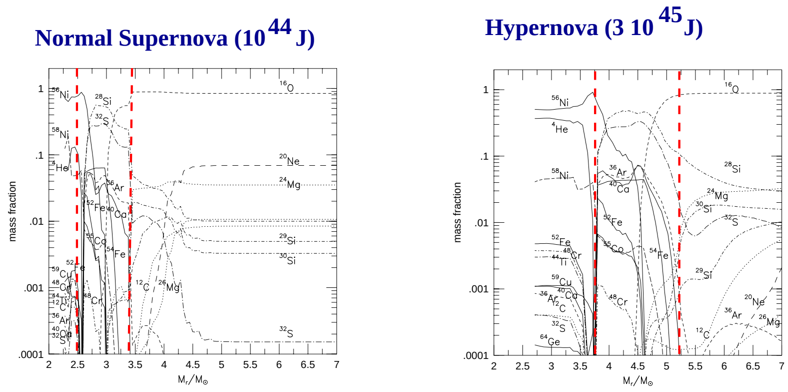
Hypernova (SN 1998bw, SN 2002ap, SN 1997ef) and (normal) Type Ic (SN 1994I) Lightcurves (Nomoto)



Hypernova Spectral Classification



Explosive Nucleosynthesis for 16 Msun Helium Star

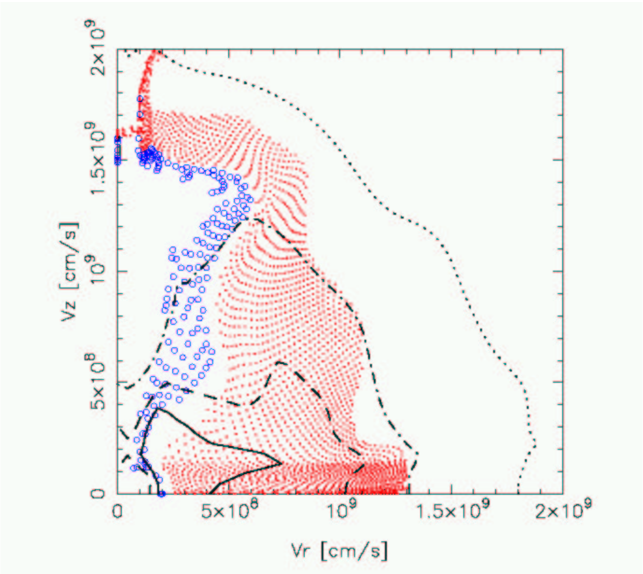

Normal Supernova (10^{44} J)

Hypernova ($3\ 10^{45}$ J)

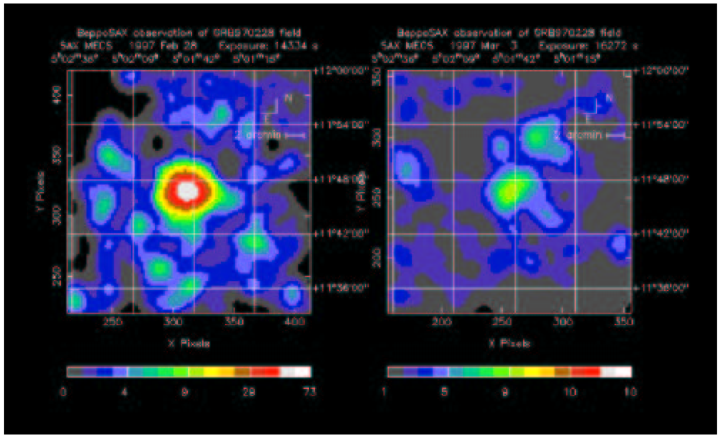
(Nomoto, Maeda et al.)

Asymmetric Hypernova Ejecta (Maeda)

- blue circles: Ni, red squares: O



Gamma-Ray Bursts



Beppo-Sax X-ray detection

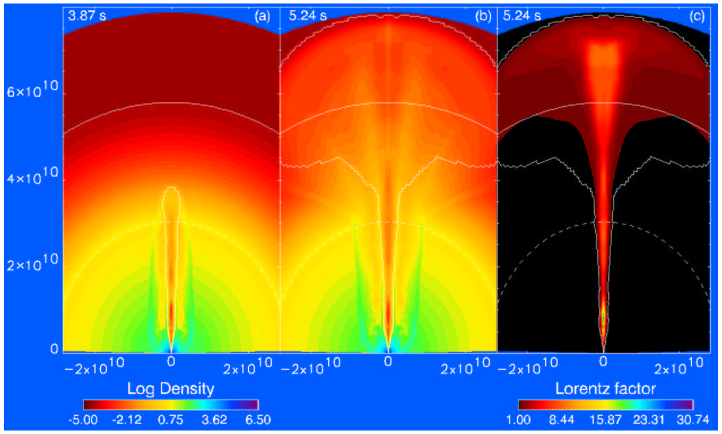


FIG. 1.— Contour maps of the logarithm of the rest–mass density after 3.87 s and 5.24 s (left two panels), and of the Lorentz factor (right panel) after 5.24 s. X and Y axis measure distance in centimeters. Dashed and solid arcs mark the stellar surface and the outer edge of the exponential atmosphere, respectively. The other solid line encloses matter whose radial velocity $> 0.3c$, and whose specific internal energy density $> 5 \times 10^{19}$ erg g^{-1}.

Collapsar Model for GRBs

Summary and Outlook

- hypernovae exist, some of which cause GRBs
- collapsar models look promising: jet can (probably) penetrate He core
- possibility of jet-driven supernovae
- unanswered questions:

  What are the progenitors?

  - ▷ have to be fairly rare, if they make up a significant fraction of luminous GRBs $(10^{-6} - 10^{-5}\,\mathrm{yr}^{-1})$
  - ▷ consistent with the rate of hypernovae
  - ▷ excludes simple (single?) type of progenitor (i.e. massive star)
  - ▷ note: all hypernovae are SNe Ic, i.e. have lost both their hydrogen and helium envelopes
  - ▷ progenitors two merged massive supergiants with He+CO cores?
  - ▷ tidally locked CO star in a very close binary ($P_{\mathrm{orb}} \lesssim 5\,\mathrm{hr}$?; e.g. Cyg X-3?)?
  - ▷ What causes the short-duration bursts?
    NS+NS/NS+BH mergers?