Nucleosynthesis of heavy elements in gamma ray bursts

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Historical GRB

- First gamma ray burst: detected by Vela satellite
- X-rays, 3-12 keV
- Gamma-rays CsI detector, 150-750 keV
Lightcurves

- Time Profile FRED: \textit{fast rise, exponential decay}
- Substructure, multiple peaks
- Time duration from 0.001 to $>1000$ s.
Typically, broken power-law (Band et al. 1993)

\[ N(\nu) = N_0 (h\nu)^\alpha \exp(-h\nu/E_0) \quad h\nu<(\alpha-\beta)E_0 \]

\[ = N_0 [(\alpha-\beta)E_0]^{(\alpha-\beta)}(h\nu)^\beta \exp(\beta-\alpha) \quad h\nu>(\alpha-\beta)E_0 \]
Swift, 2004-; detected first afterglow of a short GRB

HETE-II, 2000-; first mission dedicated for GRB; discovered about 100 of them

Chandra, 1999-; GRB991216 first emission lines in X

XMM-Newton, 1999-; GRB011211 lines of S, Mg, Ca, Ar

HST, 1990-; GRB970228 host galaxy identified

HETE-II, 1998-; first optical counterpart of a GRB

BATSE, 1991-2000; proved GRBs to be extragalactic

BeppoSAX, 1996-2002; GRB970228 first optical afterglow

ROTSE, 1998-; GRB990123 first optical afterglow

HST, 1990-; GRB970228 host galaxy identified
BATSE GRBs sample

2704 BATSE Gamma-Ray Bursts
GRB 130427A

- Detected by Swift and FermiLAT (photons with energies of 2.7 GeV)
- Associated with z Supernova, registered on 2 May, 2013
- Very close, d~3.6 Mlyrs
GRB 980425

- Optical spectrum of SN 1998bw, observed by ESO
- Explosion of massive C-O star, $E > 2 \times 10^{52}$ erg
- Nickel 56 produced
GRB 050904

- Optical afterglow, observed by Subaru
- $z=6.295$
- Metallicity $[x/H]=-2.4$, -2.3, -2.6 i -1.0 for C, O, Si i S

Kawai et al. (Nature, 2006)
Swift GRBs

- X-ray afterglows
- GRBs at large $z$ (e.g., GRB 090423, $z=8.3$)

GRB 050724 afterglow (Barthelmy et al. 2005)

GRB 130427A, associated with SN outburst on 02 May 2013
Some history of models

- Until 1992, about 100 theoretical models for GRBs were proposed.
- They differed in localisations by orders of magnitude: from Solar System to extragalactic.
- Energy requirements, flux x distance\(^2\), differed by 20 orders of magnitude.
- Examples: atmospheric lightning, magnetic reconnections in Heliopause, accretion onto a comet, starquake of a neutron star, white holes, cosmic strings...
Astro-ph/9204001

Ramesh Narayan, Bohdan Paczyński, Tsvi Piran

"Gamma Ray Bursts as the death throes of massive stars"
BH accretion

- Cosmological GRBs require powerful energy source
- Hyperaccretion helps produce an ultra-fast jet, in which the gamma rays are ultimately emitted
Progenitors range from mergers of compact stars to collapse of massive stars. Massive star must form a black hole: 10% of all collapsing stars; moreover the star must have enough rotation in its envelope to form a disk: another 10%. GRBs (due to collapsars) may therefore occur in about 1% of all core-collapse supernovae (Type I b/c). Models must account for the energy of explosion, collimation, rapid variability, range of durations, statistics.
GRB Progenitor

Disk heated by viscosity and cooled by neutrino emission

Densities $10^{10} - 10^{12}$ g cm$^{-3}$

Temperatures $kT \sim 1$ MeV

Anihilation of neutrinos and antineutrinos

Pairs $e^+, e^-$

Absorption

Scattering
Conditions in Hiperaccretion disk

- Hiperaccretion: rates of $0.01$-$10 \ M_{\odot}/s$
- Chemical and pressure balance required by nuclear reaction rates
- These are given under degeneracy of species
- Charge neutrality condition; neutrino opacities

$P$, $n$, $e^+$, $e^-$
He,
$\nu_\mu$, $\nu_e$, $\nu_\tau$
$\gamma$

Hiperaccretion disk

- Model must account for coupling between degeneracy of matter and neutrino cooling. Cooling $\rightarrow$ lower temperature $\rightarrow$ degeneracy $\rightarrow$ low density of positrons $\rightarrow$ lower cooling $\rightarrow$ higher temperature

Chen & Beloborodov (2007)
The total pressure must include the contributions from gas, radiation, and degenerate electrons:

\[ P = P_{\text{gas}} + P_{\text{rad}} + P_{\text{deg}} = \frac{k}{m_p} \rho T \left( \frac{1}{4} + \frac{3}{4} X_{\text{nuc}} \right) + \frac{11}{12} a T^4 + 2 \pi h \frac{c}{3} \left( \frac{3}{8} \pi m_p \right)^{4/3} \left( \frac{\rho}{\mu_e} \right)^{4/3} \]

where mass fraction of free nucleons depends non-linearly on density and temperature (Popham et al. 1999; Di Matteo et al. 2002; Janiuk et al. 2004)

In more advanced modeling, the equation of state must be computed numerically by solving the balance of nuclear reactions (Yuan 2005; Janiuk et al. 2007; EOS by Lattimer & Swesty 1991; Setiawan et al. 2004)
Chemical composition of the disk: e+, e-, p and n

- we assume the gas to be in beta equilibrium, so that the ratio of proton to neutron satisfies the balance between forward and backward nuclear reactions

- we assume neutrino cooling via electron, muon and tau neutrinos in the plasma opaque to their absorption and scattering

Neutrinos are formed in the URCA process (electron-positron capture on nucleons), e+e- pair annihilation, nucleon-nucleon bremsstrahlung and plasmon decay.

- leptons and baryons are relativistic and may have arbitrary degeneracy level. We compute the gas pressure using the appropriate Fermi-Dirac integrals
Equation of state

\[ P = P_{\text{nucl}} + P_{\text{He}} + P_{\text{rad}} + P_{\nu}. \]

where

\[ P_{\text{nucl}} = P_{e^-} + P_{e^+} + P_n + P_p \]

with

\[ P_i = \frac{2\sqrt{2}(m_i c^2)^4}{3\pi^2 (hc)^3} \beta_i^{5/2} \left[ F_{3/2}(\eta_i, \beta_i) + \frac{1}{2} \beta_i F_{5/2}(\eta_i, \beta_i) \right]. \]

Now the total pressure is contributed by nuclei, pairs, helium radiation, and partially trapped neutrinos.

\[ P_{\nu} = \frac{7}{8 \frac{\pi^2}{15}} \frac{(kT)^4}{3(hc)^3} \sum_{i=e,\mu,\tau} \frac{1}{2}(\tau_{a,\nu_i} + \tau_s) + \frac{1}{\sqrt{3}} + \frac{1}{3 \tau_{a,\nu_i}} \]

\[ \equiv \frac{7}{8 \frac{\pi^2}{15}} \frac{(kT)^4}{3(hc)^3} b, \]
The photons are totally trapped in the very opaque disk. The main cooling mechanism is the emission of neutrinos, via the following reactions:

- Electron and positron capture on nucleons (URCA reactions) $\rightarrow$ electron neutrinos
- Electron-positron pair annihilation (electron, muon and tau neutrinos)
- Bremsstrahlung (all neutrino flavours)

Emissivities in first two cases must be computed numerically (Itoh et al. 1996; Yakovlev 2005)
The reactions of electron and positron capture and neutron decay must establish an equilibrium

\[ p + e^- \rightarrow n + \nu_e \]
\[ p + \nu_e \rightarrow n + e^+ \]
\[ p + e^- + \nu_e \rightarrow n \]
\[ n + e^+ \rightarrow p + \nu_e \]
\[ n \rightarrow p + e^- + \nu_e \]
\[ n + \nu_e \rightarrow p + e^- \]

The rates of these reactions are given by appropriate integrals (Reddy, Prakash & Lattimer 1998) and at temperature $10^{11}$ K and densities of $> 10^{10}$ g/cm$^3$, neutrinos are efficiently produced.
Here $Q$ is neutron-proton mass difference, $|M|^2$ is averaged transition rate, and $b_e$ reflects percentage of partially trapped neutrinos ("grey body" model).
Neutrino cooling

- Other neutrino emission processes are: electron-positron pair annihilation, bremsstrahlung, plasmon decay. Rates have to be calculated numerically, with proper integrals over the distribution function of relativistic, partially degenerate species.

- \( e^- + e^+ \rightarrow \nu_l + \tilde{\nu}_l \)

- \( \gamma \rightarrow \nu_e + \tilde{\nu}_e \)

- \( n + n \rightarrow n + n + \nu_i + \tilde{\nu}_i \)
Neutrino cooling rate

The neutrino cooling rate, in \([\text{erg s}^{-1} \text{ cm}^{-3}]\) is finally given by the two-stream approximation

\[
Q_{\nu} = \frac{7/8 \sigma T^4}{3/4} \sum_i \frac{1}{\tau_{a,\nu_i} + \tau_s} + \frac{1}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3 \tau_{a,\nu_i}} \frac{1}{H}
\]

We compute the total luminosity in neutrinos by integration over the simulation volume.
Chemical balance in the disk

The ratio of protons to nucleons must satisfy the balance between number densities and reaction rates:

\[ \begin{align*}
    n_p \left( \Gamma_{p+e^- \rightarrow n+ve} + \Gamma_{p+\sim ve \rightarrow n+e^+} + \Gamma_{p+e^+ \sim ve \rightarrow n} \right) &= \\
    n_n \left( \Gamma_{n+e^+ \rightarrow p+\sim ve} + \Gamma_{n \rightarrow p+e^-+ve} + \Gamma_{n+ve \rightarrow p+e^-} \right)
\end{align*} \]

Matter must also satisfy conservation of baryon number, \( n_n + n_p = n_b X_{\text{nuc}} \).

Charge neutrality \( n_{e^-} - n_{e^+} = n_p + n_{He}^0 \) where the number of electrons in Helium: \( n_{He}^0 = 2 n_{e^-} = (1-X_{\text{nuc}}) n_b / 2 \).

\( n_{\text{nuc}} \) represents the number of nucleons.
Structure of the disk

Janiuk, Yuan, Perna & Di Matteo (2007)
Two scenarios: merger (short GRB) and collapsar (long GRB)
Equilibrium in the disk

Distribution of free protons, neutrons, electrons and positrons in the equatorial plane of the hyperaccreting disk in GRB
Degeneracy of species

Chemical potentials of protons, neutrons, electrons and positrons in the equatorial plane of the hyperaccreting disk in GRB
Electron and proton fraction

Differ due to presence of electron-positron pairs and helium in the disk

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}$$

$$Y_p = \frac{1}{1 + \frac{n}{n_p}}$$
Electron fraction distribution

Distribution of electron fraction in the equatorial plane of the hyperaccreting disk in GRB
Statistical reaction network

- Thermonuclear fusion due to capture/release of $n$, $p$, $\alpha$, $\gamma$.
- Reaction sequence produces subsequent isotopes.
- Set of non-linear differential equations solved by Euler method (Wallerstein et al. 1997 Rev. Mod. Phys.).
- Abundances calculated under assumption of nucleon number and charge conservation for a given density, temperature and electron fraction ($T \leq 1$ MeV).
Nuclear reactions may proceed with 1 (decays, electron-positron capture, photodisassociation), 2 (encounters) or 3 nuclei (3-alpha reactions).

\[ \dot{Y}_i = \sum_j N_i^j \lambda_j Y_j + \sum_{j,k} N_i^{j,k} \rho N_A \langle j,k \rangle Y_j Y_k + \sum_{j,k,l} N_i^{j,k,l} \rho^2 N_A^2 \langle j,k,l \rangle Y_j Y_k Y_l \]

where \( Y_i = \frac{n_i}{\rho} N_A \) is the abundance of \( i^{th} \) isotope,

Abundances \( \sum A_i Y_i = 1 \), electron fraction \( Y_e = \sum Z_i Y_i \)

Integrated cross-sections depending on \( kT \) are determined with Maxwell-Boltzmann or Planck statistics. Background screening and degeneracy are accounted for.
Nucleosynthesis of heavier elements in the disk surface

- we use the thermonuclear reaction network code (http://webnucleo.org) and compute the nuclear statistical equilibria established for fusion reactions.

- the reaction data are taken from the JINA reaclib online database (http://www.jinaweb.org)

- the network is appropriate for temperature ranges below 1 MeV, appropriate to the outer radii of accretion disk in GRB engine

- the mass fraction of all elements is solved for converged profiles of density, temperature and electron fraction in the disk

- parameters of the model are accretion rate, BH mass, spin, and viscosity in the disk
Most abundant isotopes synthesized in the disk. Disk model parameters:

- $M = 3 \, M_{\text{sun}}$, $\dot{M} = 0.1 \, M_{\text{sun}}/s$, $a = 0.9$

Most abundant isotopes synthesized in the disk. Model parameters:

- $M = 3 \, M_{\odot}$, $\dot{M} = 1.0 \, M_{\odot} / s$, $a = 0.9$
Main results

- We synthesized the elements up to Nickel, Cuprum and Zinc, with mass fractions above 1.e-5, or Gallium above 1.e-6, in the higher accretion rate disks.

- Free neutrons disappear above 300 rg, and heavy elements dominate above 500 rg. Below 10 rg, we have a bit more neutron rich disk than eg. Banerjee & Mukhopadhyay (2013)

- Up to 1000 rg, further layers of dominant Oxygen, Silicon and Calcium are present (Fujimoto et al. 2004). There is a trend of shifting those layers outwards, with increasing accretion rate

- Above the Iron peak, elements up to $^{84}\text{Rb}$ and $^{90}\text{Zr}$, are found with yields of 1.e-12 and 1.e-14, similarly to other works (e.g. Surman et al. 2006).

- Surman & McLaughlin (2004; 2006) described the disk outflows with spherical geometry and simple velocity profile.
2-D torus modeling

Simulation made with code HARM (High Accuracy Relativistic Magnetohydrodynamics; Gammie et al. 2003). The code provides solver for continuity and energy-momentum conservation equations.

\[(\rho u);\mu = 0 \quad T^{\mu}_{\nu;\mu} = 0 \quad p = K \rho^\gamma = (\gamma - 1)u\]

where:

\[T^{\mu\nu} = T^{\mu\nu}_{\text{gas}} + T^{\mu\nu}_{\text{EM}}\]

\[T^{\mu\nu}_{\text{gas}} = (\rho + u + p)u^\mu u^\nu + pg^{\mu\nu}\]

\[T^{\mu\nu}_{\text{EM}} = b^2u^\mu u^\nu + 1/2 b^2g^{\mu\nu} - b^\mu b^\nu\]

assuming force-free approximation.

Original code was modified to account for EOS and neutrino cooling (via internal energy update).
2-D model of GRB engine

Temperature in the innermost 50 $R_g$ of the GRB central engine. Snapshot is taken at the end of an axisymmetric GR MHD simulation (time=2000M).

Physical parameters: black hole mass: $M=10 M_{\odot}$, its spin $a=0.9$, disk mass $1.0 M_{\odot}$.

AJ & B. Kaminski; arXiv:1504.00145
2-D simulation: GRB engine
Outflows from the disk

• The outflow from accretion disk may be driven by centrifugal force and magnetic fields. Neutrino cooled disks in GRBs have faster outflows.
• The slowly accelerated outflows will allow for production of heavier elements via triple-alpha reactions up to Nickel 56 or above the Iron peak nuclei.
• The radioactive decay of certain isotopes should be detectable via the emission lines observed by X-ray satellites, such as NuSTAR. In XMM-Newton, the instrument EPIC may also be able to detect lines below 15 keV, e.g. for $^{45}$Ti, $^{57}$Mn, $^{57}$Co.
The radioactive decay of certain isotopes should be detectable via the emission lines observed by X-ray satellites. Such lines, e.g. the decay of $^{44}$Ti to $^{40}$Ca with emission of hard X-ray photons at 68 and 78 keV have been detected by NuSTAR in case of supernova remnants.

The energy band of this instrument (3-80 keV) should allow in principle for finding the X-ray signatures of other elements synthesized in the accretion disks in GRB central engines, like the radioactive isotopes of Cuprum, Zinc, Gallium, Cromium and Cobalt.
NASA's Nuclear Spectroscopy Telescope Array, or NuSTAR, has, for the first time, imaged the radioactive "guts" of a supernova remnant. The NuSTAR data are blue, and show high-energy X-rays. Yellow shows non-radioactive material detected previously by NASA's Chandra X-ray Observatory in low-energy X-rays.
Possible detection in X-rays

- NuSTAR. Launched by NASA, in 2012
- Energy 5-80 keV
- Good energy resolution
- Possible detection of X-ray photons from radioactive decay of isotopes: Ti, Co, Mn, Cu, Zn, Ga, Cr...

Iron line, detection by NuSTAR Clavin et al. (2014)
Possible detection in X-rays?

- XMM/Newton
- EPIC detector, sensitive to 15 keV, possible to find isotopes of Ti, Mn, Co

SN 1006 (Broersen et al. 2013)
Studying radioactive elements offers astronomers a more direct method for probing supernova blasts than observing non-radioactive elements. This is because this radioactive material glows with X-rays no matter what, while the X-rays detected by Chandra and other telescopes are generated only after heating with shock waves from the explosion. Because the non-radioactive material only lights up after the explosion, it does not offer a direct look at the blast itself.
Gamma Ray Bursts (GRB) are the extremely energetic transient events, visible from the most distant parts of the Universe. They are most likely powered by accretion on the hyper-Eddington rates that proceeds onto a stellar mass black hole newly formed in the center of a rotating collapsing star or via a merger of two compact stars. This central engine gives rise to the powerful, ultra-relativistic jets that are responsible for energetic gamma ray emission, as well as to the winds launched with smaller velocities from the accretion disk.

We consider the hyperaccreting disks and outflows from Gamma Ray Bursts. The torus is composed of free nucleons, Helium, electron-positron pairs, and is cooled by neutrino emission. The significant number density of neutrons in the disk and outflowing material will lead to subsequent formation of heavier nuclei. We study the process of nucleosynthesis and its possible observational consequences.
Thank you