Using ORIGEN to Help Probe Gamma-Ray Burst Mysteries

Robert B. Hayes, PhD, CHP, PE
Associate Professor of Nuclear Engineering
North Carolina State University

SCALE workshop

Introduction

- The model presented here has the potential to explain some of the highly varied nature of a portion of measured gamma ray bursts (GRBs).
  - These include the random nature of the events in terms of their parametric values and ranges.
  - Specifically many measured values of energy and time distributions, pulsing, and afterglows appear to fit those attainable with the proposed criticality model.

Oklo

- The Oklo uranium mine in South Africa is a place where the natural abundance of U235 was found to be consistently less than the 0.72 % found everywhere else on the planet
- Because the half life of U235 is almost an order of magnitude smaller than that of U238, the ratio of U235 to U238 increases in reverse time.

Oklo burn up

- By going back far enough in time, the abundance of the U nuclides would become comparable allowing rainwater to provide the moderation needed for criticality
  - The critical state would then drive out the water until more rainwater would allow the system to go critical again.
  - This probably continued many times over.
  - Kenneth Krane; Introductory Nuclear Physics; John Wiley and Sons

Oklo in space

- Just after the Super Novae (SN) (*or other source*) creation of the uranium and transuranic isotopes, most of the already radioactive elements created will quickly decay into stable atoms leaving these fissile and fissionable isotopes close to their original abundance.
- A fast reactor is possible
- Plentiful H makes a thermal system likely

TRU isotopes from SN (*or other*)

- Even if a large fraction of the Pu239 (which is fissile with a moderately long half life of just over 24 ka) were to decay away, there would still be almost the initial amount of U233 .
- U233 is fissile with a moderately long half life of just under 0.2 ma
  - with only a negligible fraction of the U235 having decayed away.

The first few years after TRU genesis

- Potential fissile isotopes could be present in the material including Pu241, Am243, Cm243, Cm245, Cm247, etc
  - while the majority of the radioactive elements would still have decayed into stable isotopes.
- This presents a dynamic reactivity dependency in terms of the fissile nuclides generated
  - Which in turn would be strongly dependent on the initial isotopic distribution source term

Criticality

- A critical system is one in which the number of neutrons generated in one generation are just equal to the number generated in a successive generation.
- The ratio of previous to successive neutron populations is a measure of reactivity often denoted as *k*.

Delayed criticality

- Delayed neutrons have very long half-lives,
  - They average in to the neutron production rate for successive generations giving the reactor a long period allowing small changes in reactivity to result in only small power changes.
- The reactivity worth of the delayed neutrons is commonly referred to as 1$ in reactivity.
- Delayed critical allows safe power reactor ops.

Prompt critical

- When a critical reactor has more than 1$ of reactivity inserted, it will become prompt critical
- Delayed neutrons are no longer needed for the chain reaction.
- Reactor doubling period is driven by moderation time scales of 10^{-8} s

Power reactors

- First bring a reactor into a zero power critical state.
- Power is then increased slowly by raising the reactivity to a delayed state while being very careful never to approach prompt criticality.
- In this regime of a supercritical state, linear power increase is carried out to first order (slow increases are achieved when total reactivity is just slightly over the critical state).

Decreasing power

- Reducing the power to a fixed level is done by bringing the reactor to a subcritical state
  - until the desired lower power level is reached
- Increasing reactivity again to the critical level ending in a steady state configuration
  - at the desired power level
- This allows lowering power to a steady state level and keeping it there

Reactivity parameters

- Other parameters which effect reactivity are specific fissile isotope distributions
- In terms of density and moderator content with their distribution and reflector material along with the presence of any neutron poisons.
- All of these parameters can be modified to either increase or decrease reactivity.

Fissile mass dependence

- The most important parameter to maintain criticality is always the total fissile mass present
  - This applies even if the fissile mass has a very low density.
- In an astrophysical environment, the minimum density could even be limited by the neutron lifetime in loosely coupled systems.

Neutronic coupling

- The coupling/buckling can readily be made more complicated by changing the geometry, density gradients, interstitial material between reactive regions and reflector distribution.
- Depending on the changes, any of these perturbations could increase or decrease system reactivity accordingly.

Fission product poisons

- Xe135 is one of many fission product poisons but it generally has the largest negative reactivity.
- It is primarily created in regions of higher fission density (initially at the center of a reactor core)
  - These locations create proportionately more fission product poisons than neighboring low fission density regions.

Xenon oscillations

- Weakly coupled thermal systems (or spatially large systems) can undergo xenon oscillations
- This sets up an oscillation whereby the less poisoned regions experience less FPP production and so undergo a relative increase in fission rate
  - when the previous FPPs are burned up, the process repeats with FPPs always being both produced and consumed in proportion to the thermal neutron flux.

Criticality approximation

- The overall neutron balance for a delayed critical system occurs when the multiplication factor *k*
- *k* is the ratio of fissions in any given generation to its subsequent generation
- At criticality, *k* is unity.
- This can be estimated for an infinite thermal reactor by $k_{\infty} = \eta f p \varepsilon$

$1 = k_{\infty} = \eta f p \varepsilon$

- η is the number of free neutrons generated per neutron absorbed by the fuel, $\eta = \eta(\mathrm{ZAID})$
- f is the fraction of thermal neutrons absorbed in the fuel,
- p is the probability that a neutron will reach thermal energy, and
- ε is the ratio of the fast to thermal neutron population

Neutron leakage

- It can be shown that the thermal neutron non leakage probability can be approximated by $P = 1/(1+\lambda^2 B^2)$
- The fast nonleakage probability can be approximated by $F_{nl}=\exp(-B^2 \tau)$. Here,
  - τ is the neutron age (in units of area)
  - λ is the thermal diffusion length and
  - B is the geometric buckling

Abundant moderation assumption implies most events should be thermal

- The key element in determining whether a system will be thermal or fast is moderator content (hydrogen which is plentiful)
- The minimum critical mass for thermal (moderated) systems tends to be more than an order of magnitude lower than for fast.
  - This in turn is because the fission cross section is often many orders of magnitude larger for slow neutrons than for fast neutrons

Starting source

- In general, a neutron source is not needed to initiate a critical event if control is not desired.
- Most fissile nuclides already have some small spontaneous fission branching ratio for decay
- A critical assembly left to itself long enough will eventually initiate the chain reaction at or above critical reactivity.

Initial gamma emission spectrum is a function of many variables

- The initial gamma distribution from fission events depends on a number of variables and so is not expected to be the same for all fission events.
- One of these variables is the actual fissile radionuclide undergoing fission.
- In principle, the fissile abundances would depend on the age of the SN excreta and the type of SN(s) originating the material

Additional gamma spectra factors (moderation, buckling, density)

- Another parameter effecting a fission gamma distribution is the average lethargy of the neutrons (fast or thermal etc).
- Not only does the initial gamma distribution depend on the fissile isotope but the time profile of the delayed gamma spectrum also changes with isotopic distributions including density gradients

Extrasolar TRU abundances

- Sneden et al (*Astrophys. J*. **591**, 936–953 (2003)). describe measured hydrogen through uranium and thorium abundances for CS 22892-052 which are similar to those found in our solar system.
- Without any form of fractionation, this distribution is not expected to generate a critical system as a homogenous mix but it could with an adequate heterogeneous mix

TRU fractionation genesis

- The standard r-process of successive neutron captures does allow for initial differential element production with the heavier elements being preferentially produced in regions of higher neutron flux
- The neutron flux during a SN or NN-NB collision is not isotropic and homogeneous
  - The TRU generated would not be homogeneous

Accidental criticalities

- One common occurrence is the pulsing of the system repeatedly going critical over time.
- Criticality heats the system to the point where the lowered density drives the system subcritical due to increased neutron leakage as both F_{nl} and P decrease with density reduction.
- In such cases, after cooling and reassembly, the system goes critical again at the higher density.

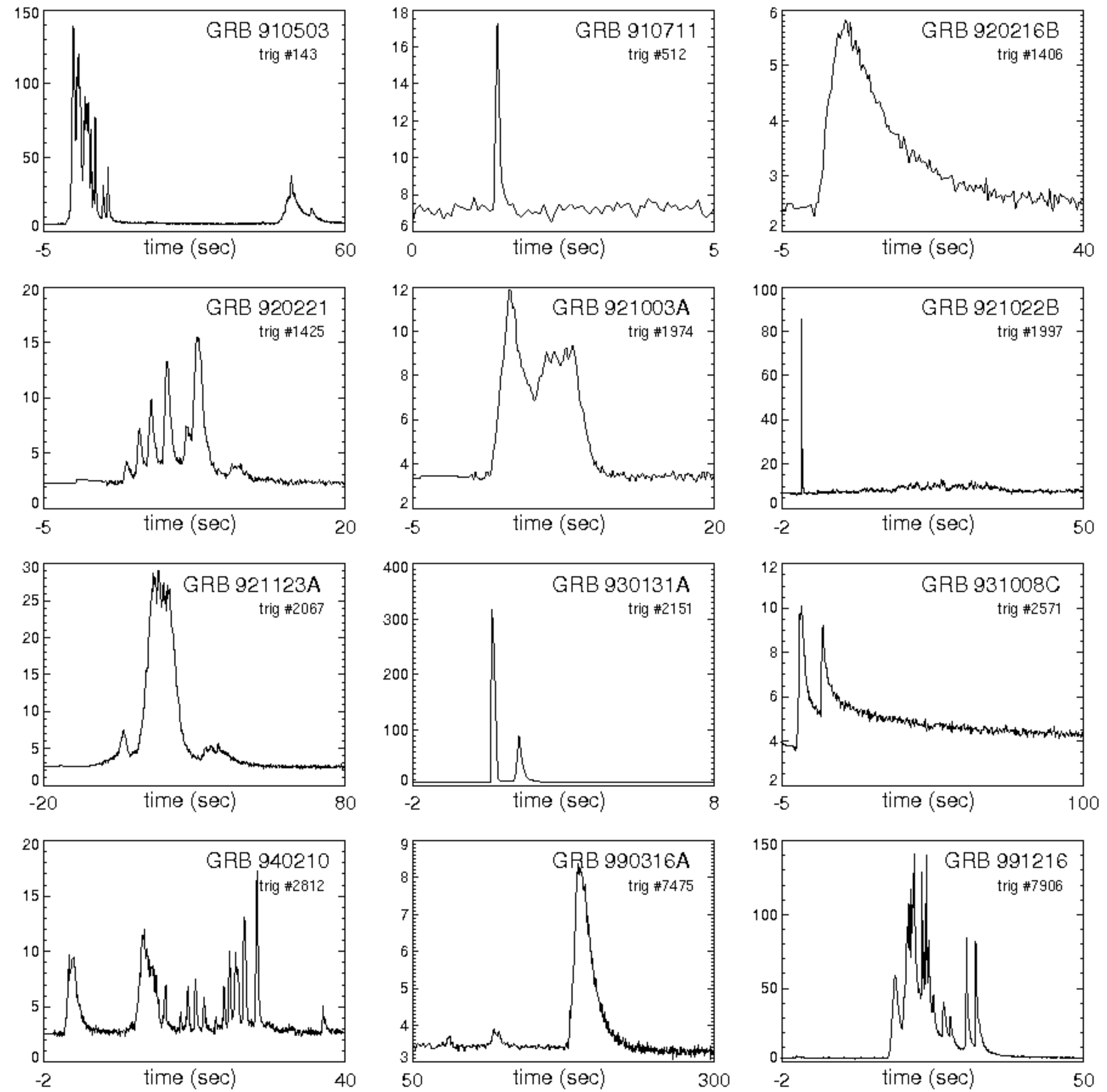
Terrestrial criticalities

- The trend so far has always been that subsequent pulses are smaller than the first.
- This is attributed to the combined effects of addition of fission products to the system
  - which are partially composed of neutron poisons
  - Ejected fissile content (in some cases) can also reduce fissile content
  - Reassembly can permit another smaller criticality

Variegated light curve pulsing

Diminishing pulses appear common not only to inadvertent criticalities but also GRBs in terms of energy output dynamics.

http://upload.wikimedia.org/wikipedia/commons/e/ef/GRB_BATSE_12lightcurves.png

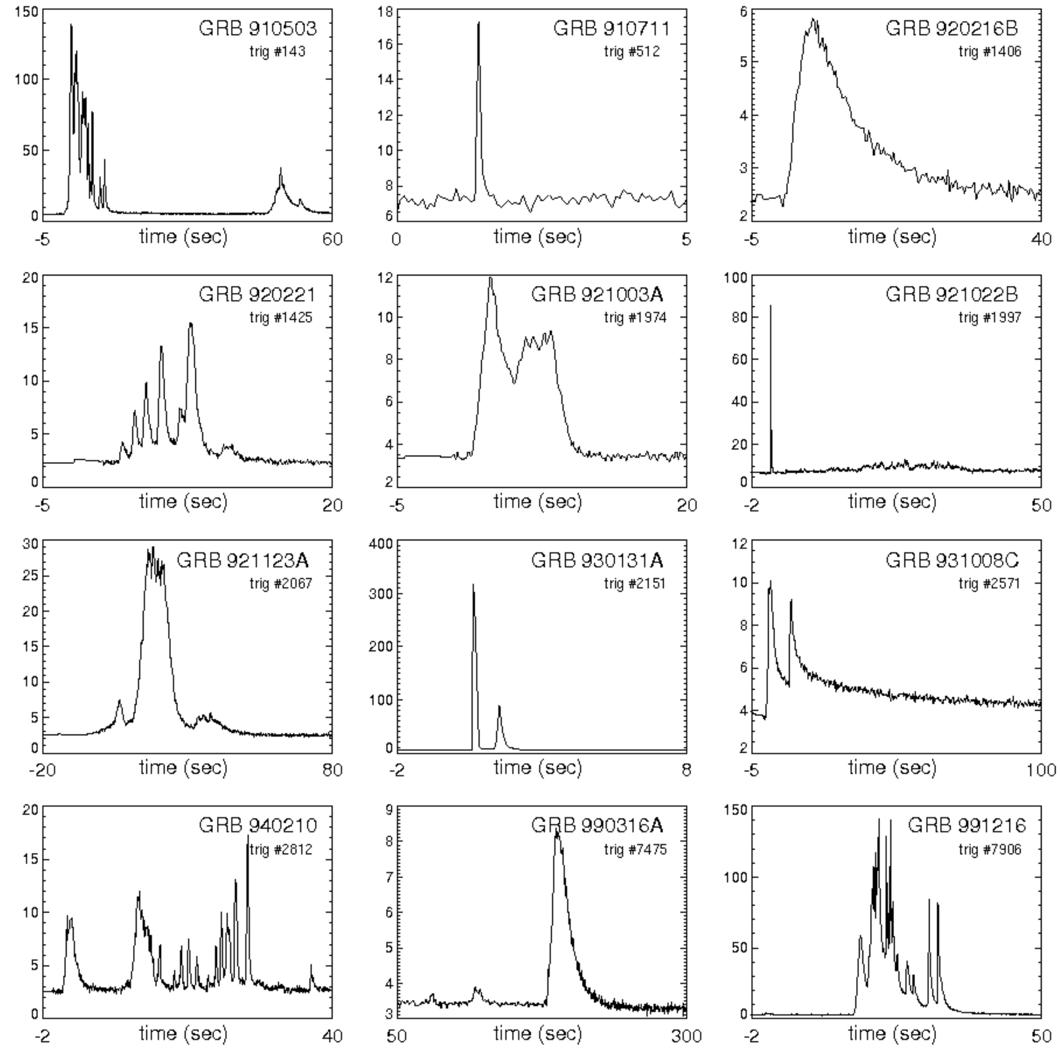


Generally attenuated pulsing

- This tendency for some gamma-ray bursts to pulse in diminishing magnitudes might be the result of a critical mass occurring in an accretion disk (or other gravitational concentrator) driving itself subcritical by the thermal expansion from the criticality event and then reassembling at a later time in a repetitive manner but with additional fission product poisons added from previous pulses.

Multi parametric

- Fuel addition rates
- Fuel addition types
- Moderator content
- Moderator type
- Material density
- Material buckling
- Feedback mechanisms



Standard r-process model

- Current model requirements to attain the isotopic distributions for actinides found in our solar system have not been made to fit better than a factor of 2.
  - We will see later this is much worse in recent years.
- Progress in explaining observations is continually ongoing
  - fission readily recognized as being an important cutoff mechanism in r-process actinide growth process

TRU genesis in neutron stars

- Other models considering actinide genesis include neutron star mergers and neutron star-black hole mergers.
- This process alone would generate substantial gamma ray spectral lines from an abundance of transuranic's generated but
  - not necessarily the criticality event prompt gamma distribution directly followed by a delayed fission product decay gamma spectra.

GRB energy distribution

- The characteristic energy distribution for GRBs has

$$N(E) \propto Ae^{-\beta E}$$

- *A* is an arbitrary magnitude parameter
- β tends to vary between around 1 or 2.
  - β exponent from BATSE has been estimated as $\beta \sim {}^{-}2$ when the energy *E* is in the range of 0.02-2 MeV
  - with β values at higher energies being $\beta \sim {}^{-}1$.

Fission vs GRB energy spectra

- GRB energy distribution
  - β exponent from has been estimated as $\beta \sim {}^{-}2$ when the energy *E* is in the range of 0.02-2 MeV
  - with β values at higher energies being $\beta \sim {}^{-}1$.

$$N_{prompt}(E) = \begin{cases} 6.6 & 0.1 < E < 0.6 \text{ MeV} \\ 20.2e^{-1.78E} & 0.6 < E < 1.5 \text{ MeV} \\ 7.2e^{-1.09E} & 1.5 < E < 10.5 \text{ MeV} \end{cases}$$

Delayed fission spectrum

- The parameter *m*(*t*) has a magnitude dependent on the total number of fissions and a known time dependence.
- The expected GRB afterglow energy distribution is approximated by $\beta \approx {}^{-}1$ in
- Post fission gamma spectrum is given by
  - AKA fission decay spectrum

$$N_{delayed}(E,t) \approx m(t)e^{-1.1E}$$

Decay magnitude time dependence

- Fission product decay is given by

$$m(t) \approx 1.26t^{-1.2}$$

- Gamma ray burst approximations is given by different sources with varying estimates for overall averages as:

$$m_{GRB}(t) \sim t^{-1/4} \quad \text{or} \quad m_{GRB}(t) \sim t^{-1.15}$$

Not as good agreement but still in the range

Beaming mechanisms

- Beta decay gamma emission is polarized
  - Wu et al. *Physical Review* **105** (4): 1413–1415, 1957.
- Gamma anisotropy can be expected in the field of a magnetar
- The resultant gamma anisotropy from a polarized radionuclide can have many parametric dependencies
  - decay energy, radionuclide spin state, external magnetic field strength and system temperature.

Predicted evidence for fission GRB

- Thermal gamma spectra will have a non beaming 2.2 MeV component
- unique beta related decay events
- Fast systems can produce fast neutron scatter event on O16 generating N16 and a proton
  - Requires the presence of oxygen in the critical mix
  - 6.1 MeV gamma and (with a lower branching ratio) 7.1 MeV gamma

GRB distribution is homogenous

- Magnetar spin axes may be highly correlated with the galactic axis
  - Similar to planetary axial correlation in solar system
  - the gamma anisotropy relative to the galactic plane could be biased to preferentially orient fission product decay gamma emission along the galactic axis.
  - Such an emission mechanism would give a more homogeneous distribution

What has been established up to now…

- Interstellar nuclear criticality events are a credible contributor to measured gamma ray bursts based on
  - initial burst gamma energy distribution up to around 10 MeV
  - Decay energy distribution
  - random after pulsing
  - the time series of many afterglow gamma distributions.

How then to guess isotopic distributions?

Assume constant mass

```
case{
% use ENDF/VII-based decay library
lib{ file="end7dec" }
% create a guest of stardust
mat{
	units=grams %gives emission per gram
	iso=[ac224=1 ac225=1 ac226=1 ac227=1 ac228=1
…………………………………………..
time{
	units=years
	t=[1 1E1 1E2 1E3 1E4 1E5 1E6 1E7 1E8 1E9 4E9]
}
	neutron {medium=2}
	gamma {continuum=yes}
print{
	nuc{ units=[moles curies] } %Ci/g
	ele{ units=[moles curies] } %Ci/g
	neutron{
		sources=yes
		spectra=yes
		detailed=yes
	}
```

Assume constant activity

```
case{
	% use ENDF/VII-based decay library
	lib{ file="end7dec" }
	% create a guest of stardust
	mat{
		units=curies %gives emission per gram
		iso=[ac224=1 ac225=1 ac226=1 ac227=1
……………………………………
time{
	units=years
	t=[1 1E1 1E2 1E3 1E4 1E5 1E6 1E7 1E8 1E9 4E9]
}
	neutron {medium=2}
	gamma {continuum=yes}
print{
	nuc{ units=[moles curies] } %Ci/g
	ele{ units=[moles curies] } %Ci/g
	neutron{
	sources=yes
	spectra=yes
	detailed=yes
}
```

What to use for the source term, maybe all the actinides?

iso=[ac224=1 ac225=1 ac226=1 ac227=1 ac228=1
am239=1 am240=1 am241=1 am242=1 am242m=1
am243=1 am244=1 am244m=1 am245=1 am246=1
am247=1 at216=1 at217=1 at218=1 be=1
bi206=1 bi207=1 bi208=1 bi209=1 bi210=1
bi210m=1 bi211=1 bi212=1 bi212m=1 bi213=1
bi214=1 bk245=1 bk246=1 bk247=1 bk248=1
bk248m=1 bk249=1 bk250=1 bk251=1 c=1
cf246=1 cf248=1 cf249=1 cf250=1 cf251=1
cf252=1 cf253=1 cf254=1 cf255=1 cm240=1
cm241=1 cm242=1 cm243=1 cm244=1 cm245=1
cm246=1 cm247=1 cm248=1 cm249=1 cm250=1
cm251=1 es251=1 es252=1 es253=1 es254=1
es254m=1 es255=1 fr220=1 fr221=1 fr222=1
fr223=1 he=1 he3=1 hg206=1 li=1 li=1
np234=1 np235=1 np236=1 np236m=1 np237=1
np238=1 np239=1 np240=1 np240m=1 np241=1
pa228=1 pa229=1 pa230=1 pa231=1 pa232=1
pa233=1 pa234=1 pa234m=1 pa235=1 pb203=1
pb204=1 pb205=1 pb206=1 pb207=1 pb207m=1
pb208=1 pb209=1 pb210=1 pb211=1 pb212=1
pb214=1 po207=1 po208=1 po209=1 po210=1
po211=1 po211m=1 po212=1 po213=1 po214=1
po215=1 po216=1 po218=1 pu236=1 pu237=1
pu237m=1 pu238=1 pu239=1 pu240=1 pu241=1
pu242=1 pu243=1 pu244=1 pu245=1 pu246=1
pu247=1 ra220=1 ra222=1 ra223=1 ra224=1
ra225=1 ra226=1 ra227=1 ra228=1 rn216=1
rn217=1 rn218=1 rn219=1 rn220=1 rn222=1
th226=1 th227=1 th228=1 th229=1 th230=1
th231=1 th232=1 th233=1 th234=1 tl203=1
tl205=1 tl206=1 tl207=1 tl208=1 tl209=1
tl210=1 u230=1 u231=1 u232=1 u233=1 u234=1
u235=1 u236=1 u237=1 u238=1 u239=1 u240=1
u241=1

Do either of these make more sense than the other?

- Constant activity implies steady state production mechanism
- Constant mass suggests fractal or dendritic type generation mechanism
- Predictions required to attain earthlike conditions
  - Lead isotopes prolly require incorporating lanthanides
  - Th232:U238 ~ 3
  - U238:U235 ~138
  - Th232:Th230 ~ 5000

So what does ORIGEN say about 4E9 yr?

- Output results from constant isotopic mass (1 g)
  - Th232:U238 ~ 3 (basically identical to prediction)
  - U238:U235 ~ 14 (off by an order of magnitude from 138)
  - Th232:Th230 ~ 2E5 (over 5E3 by factor of 40)
- Output results from constant isotopic activity (1 Ci)
  - Th232:U238 ~ 0.5 (off by almost an order)
  - U238:U235 ~ 2 (off by almost 2 orders)
  - Th232:Th230 ~ 1E-6 (11 orders of magnitude off)

Conclusions

- ORIGEN allows the possibility of generating a time dependent actinide mix for GRB source terms (ignoring lanthanides)
  - Best guess is constant isotopic mass distribution
- Enables an approach to modeling GRB spectra
- After sufficient distributions of simulated criticality based GRB have been assembled, these can be compared to empirical measurement (BATSE, FERMI, SWIFT etc.).