Calculations of Gamma Ray Dose from Gamma Ray Bursters and Nearby Supernovae

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INTRODUCTION

Supernovae and gamma ray bursters (possibly caused by "hypernovae") are the most energetic known events in the Universe. Supernovae release approximately 10^{51} ergs of energy in the form of photons, neutrinos, and kinetic energy imparted to debris from the explosion. Hypernovae release approximately 10^{53} ergs of gamma ray energy alone (1). Some researchers have speculated that nearby supernovae and hypernovae may have caused mass extinctions on earth because of the tremendous amount of energy released during these events and their relative frequency on geologic timescales.

In this paper, I briefly describe the origins and mechanisms of these two events, the gamma radiation dose in space resulting from supernovae and GRB at a variety of distances from the earth, and the corresponding dose rates at the Earth's surface. I then calculate dose rates for organisms living at various depths in water and discuss the implications of these dose measurements for life on Earth.

Supernovae

Supernovae are the result of stellar explosions that take place late in the life of a massive star. The two main categories of supernovae are Type I and Type II supernovae. Type I supernovae are thought to occur in binary stellar systems in which a white dwarf captures material from its companion star. Once the white dwarf has accumulated enough matter, it "ignites" in a massive thermonuclear explosion. Type I supernovae eject about one solar mass of matter into space, the kinetic energy of which accounts for the majority of energy released in these events (2).

Type II supernovae occur in large stars (>18 solar masses) whose cores are no longer producing sufficient energy to balance the effects of gravitation. These stars collapse with the outer layers rebounding off of the collapsed core into space. Most of the energy released in Type II supernovae is in the form of neutrinos (2**)** with the balance emitted in the forms of kinetic energy of ejected matter and photons/gamma rays.

The overall rate of supernovae in the Milky Way Galaxy is about 1-2 per century, most of which occur in spiral arms or in the galactic bulge. It is thought that most extra-solar cosmic rays originate as debris from supernovae. Supernovae release about 10^{51} ergs of total energy in the space of a few weeks, about 0.01% (or about 10^{47} ergs) of which is emitted in the form of high-energy photons (3**)**. Some researchers have speculated that supernovae may be associated with mass extinctions noted in the terrestrial fossil record (4, 5**)** although this may never be known with any high degree of certainty.

Gamma Ray Bursters / GRB

Gamma ray bursters (GRB) were first identified over 30 years ago but their origin was unknown until very recently. There is a growing consensus that they are the result of extremely high-energy supernovae events that have been dubbed "GRB" and they can be detected at cosmological distances, but many other mechanisms have been suggested (1**)**. For the purposes of this paper, which is primarily concerned with the effects of gamma radiation on life, the exact GRB mechanism is not as important as the energy released in gamma rays from these events. Astronomers have calculated that about 10^{53} ergs of gamma ray energy is released during GRB explosions. GRBs appear to occur about once every 10^6 to 10^7 years in galaxies similar to the Milky Way and have relatively short periods of maximum emission. One researcher (6) has speculated that GRBs may have periodically sterilized all planets in the Milky Way. This speculation will be discussed later in this paper.

There is still debate regarding whether or not GRB gamma rays are emitted isotropically or are beamed (1**)**. If GRB are beamed, their overall energy requirements are much lower because all measured gamma ray fluxes are concentrated into a beam that may cover only 0.1% of a sphere. If this is the case, GRB may simply be supernovae in which some as-yet-unknown mechanism results in this high degree of collimation. In addition, beaming of GRB would result in a much higher actual event rate because we would be able to detect only a small fraction of the actual events. However, for the purposes of calculating gamma radiation dose and periodicity, both cases can be treated identically since the attenuation due to distance will remain the same as will the observed periodicity in the Milky Way.

Dose calculations s

Radiation dose is simply a measure of energy deposition per unit of mass. One Gy is the deposition of 1 J kg^{-1} or 10^4 ergs gm^{-1}. Therefore, to calculate the energy deposition in tissue at any given distance from a hypernova or supernova, one must calculate the energy flux at that distance from the event and then determine the attenuation due to atmospheric shielding. The density of matter in interstellar space varies widely, but is typically less than 1 hydrogen atom per cm^3. The density of matter in intergalactic space seems to be less than $3x10^{-11}$ hydrogen atoms per cm^3 [7]. This means that, in a distance of $6.022x10^{23}$ cm (about 195,000 pc, more than three times the distance to the Magellenic Clouds) there will be one gram of hydrogen or less in a column of 1 cm^2 cross-sectional area. GRBs at cosmological distances are much further away, but the gamma rays traverse a much more rarified medium. The matter interposed between the Earth and a GRB at a distance of 10^9 pc would be on the order of micrograms. The highest atom density commonly found inside of galaxies, from 40-125 atoms per cm^3, is in hydrogen clouds (7). At a density of 125 atoms per cm^3, there would be about $6.4x10^{-4}$ grams of hydrogen per parsec in a 1 cm^2 column. These low mass densities suggest that attenuation of gamma radiation both within and outside our galaxy is not important in calculating dose from gamma radiation from these events.

Astronomical distances are typically reported in units of parsecs (the distance at which we note a parallax shift of one arc-second with a baseline of two astronomical units). One parsec is approximately 3.26 light-years or about $3.08x10^{18}$ cm. A sphere of this radius has a surface area of about $1.2x10^{38}$ cm^2 using the formula $A=4\pi r^2$. This means that, in the case of a GRB, the available energy has to fill this area. At a distance of one parsec, the energy flux from a GRB is about $8.36x10^{14}$ ergs cm^{-2}, giving a radiation dose rate of $8.36x10^{10}$ Gy. Similar calculations for supernovae indicate that, assuming a supernova gamma energy of 10^{47}ergs, gamma radiation dose at the top of Earth's atmosphere will be about six orders of magnitude lower. These doses then follow the inverse square law for supernovae and GRB at greater distances. It is noteworthy that a GRB at the distance of the Andromeda Galaxy, about 1 MPc, will deliver a gamma ray dose of nearly 0.1 Gy, twice the allowed annual dose for radiation workers in the US.

Calculating the typical interval between such events is not simple because the large, short-lived stars that give rise to supernovae and GRB do not stray far from the spiral arms in which they were born while the solar system passes through spiral arms as it circles the galaxy. Spiral arms travel as density waves rather than as discrete particles in independent orbits, so they rotate at a somewhat slower rate than the individual stars of which they are comprised. In addition, the solar system passes through the galactic plane in its orbit about the galaxy, adding further complexity to reaching an exact solution to this problem. Accordingly, many simplifications are used to determine the approximate periodicity of these events at a variety of distances from the solar system. For this paper, I have used the periodicity relationship developed by Terry and Tucker (5) to determine the frequency with which supernovae and GRB are expected to occur within a given distance of the solar system. This relationship is:

$$N(R_0 t) = 2x10^{-12}\ ftR_0^3 \qquad (1)$$

where $N(R_0t)$ is the number of supernovae in a volume of space with a radius of R_o light years over a period of t years. The term *f* refers to the frequency with which supernovae or GRB occur in the Milky Way Galaxy (about 0.02 yr^{-1} and 10^{-6} yr^{-1}, respectively. Solving this equation for t yields the average interval between such events. Table 1 shows gamma ray doses in space and approximate intervals between events at these distances for supernovae and GRB at various distances from earth.

Radiation dose at the surface of the Earth is much lower than at the top of the atmosphere because of the attenuation provided by air. This attenuation is calculated using the shielding equation:

$$D_{sh} = D_{unsh} B e^{-\mu x} \qquad (2)$$

where μ is the attenuation coefficient, x is the thickness of the shield, *B* is the buildup factor, and *D* refers to the shielded and unshielded dose as indicated by the subscripts. For the purposes of this paper, the units for μ are cm^2 g^{-1} which were multiplied by the density thickness of the atmosphere, 1000 g cm^2. Similar calculations were performed for attenuation of surface radiation dose by water. The values for attenuation coefficients and buildup factors came from Schleien (8)and were checked against values determined using XCOM

(9).

GRB gamma energy	10^{53} ergs			SN gamma energy	10^{47} ergs		
GRB Distance (parsecs)	**Dose (Gy) (space)**	**Dose (Gy) (sea level)**	**Mean interval (yrs)**	**SN Distance (parsecs)**	**Dose (Gy) (space)**	**Dose (Gy) (sea level)**	**Mean interval (yrs)**
10	10^{9}	100	10^{13}	10	10^{3}	10^{-4}	10^{9}
100	10^{7}	1	10^{10}	100	10^{1}	10^{-6}	10^{6}
1,000	10^{5}	0.01	**Note 1**	1,000	10^{-1}	10^{-8}	**Note 1**
10,000	10^{3}	10^{-4}	~ $2x10^{6}$ **(Note 1)**	10,000	10^{-3}	10^{-10}	**Note 1**

Table 1: Gamma ray burst and supernova gamma radiation dose versus distance.

Note 1: Exact determination of the mean interval of these events at distances of greater than about 600 parsecs (the approximate thickness of the galactic plane) cannot performed using equation 1 because the local stellar neighborhood is not isotropic beyond this distance.

The value of μ changes according to the gamma ray energy and the absorber. Attenuation was calculated for a variety of gamma ray energies from 1 MeV to 1000 MeV. The most penetrating gammas are those with an energy of about 50 MeV. Above this energy level, photo-neutron effects and pair production become increasingly efficient at reducing dose due to gamma radiation, although other radiations may reach the ground in the form of a cosmic ray air shower. If we assume that all SN and GRB gamma ray energy is emitted in the form of 50 MeV photons, we arrive at the highest possible dose from these events. This most conservative estimate will be used for further calculations of dose rate with the knowledge that actual gamma ray dose rates will be markedly lower because SN and GRB gamma ray spectra seem to peak at energies of a few hundred KeV. Table 2 shows the calculated radiation doses at sea level and a variety of water depths from SN and GRB delivering a radiation dose off 10^4 Gy to the top of the atmosphere, assuming all energy deposited is in the form of 50 MeV photons. This is an event that would occur about every one million years as a GRB and about every 2 billion years as a SN.

Dose at top of atmosphere	Atmospheric density thickness	Attenuation Coefficient (50 MeV gamma) (air / H_2O)	Attenuation Coefficient (500 KeV gamma) (air / H_2O)
10^6 Gy	1000 (gm/cm^2)	0.0161 / 0.0167 cm^2 g^{-1}	0.0869 / 0.0966 cm^2 g^{-1}

Gamma Dose (sea level)	Water Depth (m)	Gamma Dose (Gy) 50 MeV γ	Gamma Dose (Gy) 500 KeV γ
	0.0	1.82E-32	1.82E-32
50 MeV γ 0.0102 Gy	0.1	1.54E-32	6.92E-33
	0.2	1.30E-32	2.63E-33
500 KeV γ $1.8x10^{-32}$ Gy	0.5	7.89E-33	1.45E-34
	1.0	3.42E-33	1.16E-36
	2.0	6.45E-34	7.40E-41
	5.0	4.30E-36	1.92E-53
	10.0	1.02E-39	2.03E-74

Table 2 :Radiation dose at sea level and versus depth in water for gamma ray photons with energies of 50 MeV and 500 KeV.

Other sources of radiation exposure from GRB and SN

Gamma rays surviving attenuation by the atmosphere provide only a part of the total radiation dose from GRB and SN events. Other sources of exposure include the following:

- High-energy charged particles and relativistic neutrons
- Neutrinos
- Secondary photons from interactions of emitted particles with the interstellar medium or SN/GRB debris
- Secondary particles and photons generated via interactions in the atmosphere (cosmic ray air showers)

- Formation of elevated levels of cosmogenic radionuclides from cosmic rays and cosmic ray shower particles

High-energy charged particles will be deflected to some extent by the galactic magnetic field and may be slowed down via interactions with the ISM. Although neutrons have a half-life of about 10.25 minutes outside of an atomic nucleus (10), the time dilation experienced by highly relativistic neutrons may permit them to travel 10 parsecs or so before undergoing decay (11). Up to half the energy of SN and an unknown fraction of GRB energy is emitted in the form of neutrinos. Some have speculated about the biological effect of neutrinos, including those from supernovae (12, 13), but it seems safe to say that, at present, little is actually known about their potential biological effects. Gamma rays thought to originate from the interactions of SN debris with the ISM or with SN debris have been detected on Earth (11), albeit from very distant SN and their contribution to overall gamma ray dose from nearby events has not been estimated. Finally, the generation or cosmic ray air showers from cosmic rays and high-energy photons is well-known although the contribution of this source of radiation dose in the instance of high-dose events has not been calculated yet, either. For this last source of radiation exposure, high-energy photons interact via pair production and photo-neutron interactions, generating secondary particles and photons which continue interacting until all the incident photon energy has been spent or until the air shower reaches the ground. Particles generate air showers in a similar manner. The relative contributions of all these sources of exposure have not been quantified so their relative importance as sources of radiation dose cannot be estimated at this time. This is, however, the subject of ongoing research by me and initial estimates should be available in the near future.

Discussion

It is immediately obvious that a GRB explosion can deliver a very high gamma radiation dose to the solar system from any location in our galaxy. In fact, this dose is likely to be lethal to virtually any organism experiencing it. This would be expected to occur about every one million years on average and is not dependent on the location of the solar system with respect to spiral arms. Supernovae can deliver gamma radiation dose of similar magnitude from a distance of about 1 parsec and would be anticipated to occur about 10 billion years. Over this distance scale, the position of the solar system with respect to spiral arms is very important because 1 parsec is less than the distance between spiral arms. It therefore seems unlikely that gamma radiation from nearby supernovae has unduly influenced the radiation environment on Earth.

The periodicity of GRB that could generate a lethal dose of radiation at the surface of the Earth is very long, about one every 14 billion years. Considering that, until relatively geologically recently (about 400 million years ago) life lived almost exclusively in the water, it seems unlikely that nearby GRBs have ever resulted in widespread extinctions due to radiation effects. In addition, the short outburst time of GRBs (about 30-60 seconds) would prevent them from directly affecting more than half of the Earth at any time, further suggesting they are not responsible for mass extinctions. However, GRBs and SN can raise background radiation levels on Earth significantly without causing deaths. In fact, GRB at a distance of about 1000 pc, occurring about every 14 million years, would raise radiation levels in the top meter of water to about 1.6 mGy, in excess of the mutation doubling dose of 1 mGy (14, 15) and dose rates to terrestrial organisms would be even higher. These dose rates and time scales may have implications with respect to radiation dose response in modern organisms. In addition, the very high dose rates at relatively frequent intervals in space may have further implications for the transport of living organisms to Earth from elsewhere in the solar system or the galaxy. Both of these are discussed further in the following sections.

Radiation dose-response effects

Modern organisms respond to radiation damage through a variety of damage repair mechanisms. There is currently some debate regarding the ability of these mechanisms to accurately repair damage from radiation levels greater than the current background levels on Earth with some suggesting that exposure to any elevated radiation levels is harmful and may caused added risk. Recent work (16) has shown that life evolved under higher background radiation levels than currently exist, suggesting that repair mechanisms may have retained the ability to accurately repair higher levels of radiation-induced DNA damage. However, background radiation levels from terrestrial sources have experienced a steady decrease over the last 2 billion years and it is also possible that repair mechanisms have concurrently become less efficient.

If, however, nearby cosmic events have periodically raised background radiation levels by a few mGy at average intervals of several million years, this would provide a relatively constant (on evolutionary time scales) elevated radiation dose rate. This, in turn, may provide a mechanism by which DNA damage repair mechanisms might retain the ability to accurately repair higher levels of radiogenic DNA damage than currently exist, even in the face of ever-decreasing levels of terrestrial background radiation. In other words, the presence of relatively frequent SN and GRB explosions may periodically “reset” the threshold below which there is no additional risk from radiation exposure.

Transport of living organisms through space

There has been recent speculation regarding the potential for terrestrial life to have first evolved elsewhere in the solar system or galaxy, being transported to Earth on a meteor or comet. Calculations of radiation dose in space from GRBs show that doses of about 200 Gy from anywhere in the galaxy occur about every one million years. This dose is lethal to all known forms of life, suggesting that living organisms "hitching rides" on comets or meteors would have to do so on bodies large enough to allow for relatively deep burial and shielding by overlying cometary or meteoritic matter. Specifically, doses of about 10 Gy would penetrate to at least a depth of 50 cm in rock meteors (assuming a density of 2.6 gm cm^{-3}) and to a depth of about 1.75 m in comets (assuming a density of 1.0 gm cm^{-3}). This neglects the effects of buildup. These results are provided in Table 3. This suggests that any stony bodies of less than a meter in diameter or any icy bodies less than 3.5 meters in diameter are unlikely abodes on which living organisms can travel from planet to planet unless their travel time is less than about one million years.

The size of spaceborne debris varies widely, but, in general, smaller bodies are far more common than larger ones. In addition, smaller bodies rotate more rapidly than do larger ones as a general rule. This suggests that the possibility of living organisms surviving long journeys between planets or between stars is very small because most such organisms are likely to be present on small, rapidly rotating bodies and would thus be exposed to very high radiation doses at frequent intervals during their journey through the solar system or through the galaxy.

Not considered in this paper is the effect of neutrino radiation on terrestrial life or on life contained in meteors or comets. Although neutrinos interact very weakly with matter, supernovae release about 10^{53} ergs of neutrino energy. In addition, due to their weak interactions, neutrinos will be largely unaffected by intervening matter and will irradiate all parts of meteors, comets, or planets equally. Therefore, the potential exists, depending on the interaction cross-section, neutrino spectrum, and relative biological effectiveness, neutrinos may provide the most significant radiation dose from supernovae. In addition, if GRBs are, indeed, an energetic variant of SN, they may produce considerable radiation dose from neutrinos, too. These issues are not considered quantitatively in this paper, but are the subject of on-going work that will be reported in the future.

Dose (outer surface) (Gy)	**Density thickness (gm/cm^2)**	**Depth (rock) (cm)**	**Dose (Gy) 50 MeV μ=0.0232 cm^2 g^{-1}**	**Dose (Gy) (500 KeV) μ=0.0871 cm^2 g^{-1}**
10^6	1	0.385	$9.77x10^5$	$9.17x10^5$
10^6	2	0.769	$9.55x10^5$	$8.40x10^5$
10^6	5	1.923	$8.90x10^5$	$6.47x10^5$
10^6	10	3.846	$7.93x10^5$	$4.19x10^5$
10^6	20	7.692	$6.29x10^5$	$1.75x10^5$
10^6	50	19.238	$3.13x10^5$	$1.28x10^4$
10^6	125	48.08	$5.50x10^4$	18.7
10^6	200	76.92	$9.66x10^3$	$2.72x10^{-2}$
10^6	1000	384.6	$8.40x10^{-5}$	$1.49x10^{-32}$

Table 3 : Attenuation of 50 MeV gammas in rock meteors.

Conclusions

GRBs located anywhere in the galaxy can deliver a lethal radiation dose in space and SN can deliver an elevated gamma radiation dose over relatively short distances and concomitantly long time intervals. However, because of the attenuation provided by the Earth's atmosphere, it is unlikely that such the direct gamma ray dose from such events is sufficient in and of itself to cause mass extinctions on Earth. Obviously, these events occur and any planets unlucky enough to be nearby will be sterilized, but the probability of one of these events occurring near Earth are very low. However, even at greater distances, these events have the ability to raise background radiation levels on Earth considerably above the norm, providing a continuing challenge to life's DNA repair mechanisms over time. This, in turn, suggests a reason for these repair mechanisms to be able to effectively repair damage resulting from radiation doses above current background levels. In addition, the very high radiation dose rates from these events may help to place limits on the ability of living organisms to be transported about the galaxy except over relatively short distances.

There are, of course, other sources of radiation dose from such energetic events. Further research should help to resolve questions regarding the probable radiation dose from all sources of exposure from SN and GRB events and will help to better determine their impact on terrestrial background radiation levels.

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