Paper

# GAMMA AND NEUTRINO RADIATION DOSE FROM GAMMA RAY BURSTS AND NEARBY SUPERNOVAE

P. Andrew Karam*

*Abstract*—**Supernovae and gamma ray bursts are exceptionally powerful cosmic events that occur randomly in space and time in our galaxy. Their potential to produce very high radiation levels has been discussed, along with speculation that they may have caused mass extinctions noted from the fossil record. It is far more likely that they have produced radiation levels that, while not lethal, are genetically significant, and these events may have influenced the course of evolution and the manner in which organisms respond to radiation insult. Finally, intense gamma radiation exposure from these events may influence the ability of living organisms to travel through space. Calculations presented in this paper suggest that supernovae and gamma ray bursts are likely to produce sea-level radiation exposures of about 1 Gy with a mean interval of about five million years and sea-level radiation exposures of about 0.2 Gy every million years. Comets and meteors traveling through space would receive doses in excess of 10 Gy at a depth of 0.02 m at mean intervals of 4 and 156 million years, respectively. This may place some constraints on the ability of life to travel through space either between planets or between planetary systems. Calculations of radiation dose from neutrino radiation are presented and indicate that this is not a significant source of radiation exposure for even extremely close events for the expected neutrino spectrum from these events.**

**Health Phys. 82(4):491–499; 2002**

**Key words: radiation, cosmic; radiation, background; linear hypothesis; gamma radiation**

## INTRODUCTION

SUPERNOVAE (SN) and gamma ray bursts (GRB) are the most energetic known events in the Universe. Supernovae release between $10^{43}$ and $10^{44}$ J of energy in the form of photons, neutrinos, and kinetic energy imparted to debris from the explosion. Of this, about $10^{42}$ J are in the form of gamma radiation, most of which comes from the decay of radioactive atoms synthesized during the SN explosion and emitted during the first few months post-detonation. Gamma ray bursts release the isotropic equivalent of about $10^{53}$ ergs of gamma ray energy (Wheeler 2000). Some researchers have speculated that nearby supernovae and GRBs may have caused mass extinctions on Earth, although such events are not the point of this paper.

This paper briefly describes current hypotheses regarding the origins and mechanisms of these two events, the gamma radiation dose in space resulting from supernovae and GRBs at a variety of distances from the Earth, and the corresponding dose rates at the Earth's surface. It then describes gamma radiation dose to organisms living at various depths in water and discusses some implications of these events for life on Earth. Calculations of radiation dose from SN-spectrum neutrinos are also presented for the first time, confirming earlier work (Cossairt and Marshall 1997) suggesting that neutrinos are not a significant source of radiation exposure, even from such energetic events. Finally, some other sources of radiation exposure from SN and GRBs are discussed qualitatively because a quantitative treatment is beyond the scope of this paper and, in some cases, does not seem to be called for.

This paper will follow the astronomical convention of reporting distances in units of parsecs (pc). One parsec is the distance at which an object will shift an angular distance of one arc-second with a baseline of two astronomical units. In other words, viewing a star at this distance from opposite sides of the Earth's orbit will cause a shift of one arc-second. One parsec is equal to 3.26 light-years and $3.08 \times 10^{16}$ m.

### The source term

**Supernovae.** Supernovae are 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 (Binney and Merrifield 1998). Type I supernovae typically produce much larger amounts of heavy radioactive elements than do Type II supernovae, and these elements are the primary source of radiation

* University of Rochester, Department of Environmental Medicine, 601 Elmwood Avenue, Box HPH, Rochester, NY 14642.

For correspondence or reprints contact P. A. Karam at the above address, or email at Andrew_Karam@URMC.Rochester.edu.

(*Manuscript received* 29 *August* 2000; *revised manuscript received* 23 *July* 2001, *accepted* 10 *November* 2001)

0017-9078/02/0

dose from these events. Type I supernovae progenitor stars are thought to blow themselves apart in the explosion without leaving a neutron star or black hole as a remnant (Wheeler 1990).

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 and the outer layers rebound off of the collapsed core into space. During this collapse, a neutron star is formed of about one solar mass (roughly $2 \times 10^{33}$ g) containing about $10^{57}$ neutrons. Each neutron will emit a neutrino when it is formed with an average energy of between 5 and 15 MeV (Sutaria and Ray 1997; Schramm and Brown 1990). These neutrinos account for most of the energy released during a supernova explosion.

Supernovae release about $10^{44}$ J of kinetic energy, a few times $10^{45}$ J of neutrino energy, and about $10^{40}$ J of prompt photon energy (Wheeler 1990). In addition to the radiation released directly in the form of photons, neutrinos, and charged particles, SN produce large amounts of unstable nuclei that will subsequently decay radioactively and many of which emit gamma radiation. In particular, $^{56}$Ni ($t_{1/2}$ = 5.9 d) will be produced in abundance, decaying to $^{56}$Co ($t_{1/2}$ = 77.3 d). The $^{56}$Co decays in turn to stable $^{56}$Fe with the emission of a positron and multiple gammas. These, and other radioactive decays will have a peak gamma ray luminosity of about $10^{34}$ J s$^{-1}$ and, over 100 d, will release about $10^{42}$ J of energy (Hoflich et al. 1998). Radiation dose from SN-produced radioactivities is the subject of another paper (Karam 2002) and will not be discussed further.

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. Some researchers have speculated that supernovae may be associated with mass extinctions noted in the terrestrial fossil record (Ellis et al. 1996; Terry and Tucker 1968), although this may never be known with any high degree of certainty.

**Gamma ray bursts.** Gamma ray bursts were first identified over 30 y ago, but their origin was unknown until very recently. The exact mechanism(s) by which such prodigious amounts of energy are produced are still not agreed-upon by GRB workers. What is generally agreed is that they can be detected at cosmological distances (in other words, at distances of billions of parsecs). 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 the isotropic equivalent of $10^{45}$ to $10^{47}$ J of gamma ray energy is released during GRB explosions, and they seem to occur about once every $10^6$ to $10^7$ years in galaxies similar to the Milky Way with periods of maximum emission lasting about 30–60 s (Wheeler 2000). One researcher (Annis 1999) 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 collimated in some way (Wheeler 2000). If they are collimated, their overall energy requirements are much lower because all measured gamma ray fluxes are concentrated into a beam that may cover only a small fraction of a sphere.

## DOSE CALCULATIONS

### Gamma radiation dose in space

Radiation emitted by any object in the galaxy must first traverse the interstellar medium to reach the earth. However, the average density of even relatively dense gas clouds is still a near-perfect vacuum, and there is very little actual attenuation that occurs.

The density of matter in interstellar space varies widely, but is typically less than $10^6$ hydrogen atoms per m$^3$ (about 1 atom cm$^{-3}$). This means that in a distance of $6.022 \times 10^{21}$ m (about 195,000 pc) there will be 1 g of hydrogen or less in a column of 1 cm$^2$ cross-sectional area. Since our galaxy is about 25,000 pc in diameter, the attenuation of gamma radiation by the interstellar medium is negligible. The highest atom density, from $40–125 \times 10^6$ atoms per m$^3$ commonly found inside of galaxies is in hydrogen clouds (Harwitt 1982). At a density of $125 \times 10^6$ atoms per m$^3$, there would be about $6.4 \times 10^{-4}$ g of hydrogen per parsec in a 1-cm$^2$ column. Accordingly, gamma ray attenuation by the interstellar medium is insignificant and will not be considered further. In these cases, a cross-sectional area of 1 cm$^2$ is used because attenuation coefficients are typically reported in units of cm$^2$ g$^{-1}$.

It is also important to note that the duration of these events varies. Because of the relatively short GRB outburst time, no more than one half of the earth would be exposed to radiation, and the actual exposure will vary according to the location of the burst in the sky.[†] By comparison, SN will irradiate the entire planet, although no single location will be subject to more than one half the integrated radiation exposure because of the shielding provided by the Earth.

A sphere with a radius of 1 parsec has a surface area of about $1.19 \times 10^{34}$ m$^2$ using the formula $A = 4\pi r^2$. The available energy has to fill this area. The energy fluence ($\phi_E$) at the top of the Earth's atmosphere from a GRB at a given distance ($D$) in parsecs from the earth is calculated as

$$\phi_E = \frac{E_{GRB}}{1.19 \times 10^{38}\ \mathrm{cm}^2 D^2_{pc}}. \qquad (1)$$

At a distance of $10^4$ parsecs (roughly the distance from the Solar System to the galactic center), the gamma energy fluence from a GRB with the isotropic equivalent energy of $10^{46}$ J is about 8,400 J m$^{-2}$. The absorbed dose,

[†] For example, a gamma ray burst directly overhead will deliver the highest dose while one near the horizon will have more attenuation because of the greater path length through the atmosphere.

of course, will depend on the energy spectrum of the gamma radiation and the composition of the absorber.

## Gamma radiation dose at sea level

The atmospheric column density at sea level is about 1 kg $cm^{-2}$. Using standard shielding calculations, it appears as though the earth's atmosphere is sufficient to reduce incident radiation exposure by about 10 orders of magnitude. However, because of the great thickness of the atmosphere (about 200 km), its varying density, and the geometry (an effectively infinite source of parallel gamma rays), conventional shielding calculations may not provide reasonable answers for gamma ray attenuation.

In sharp contrast, Scalo and Wheeler (2002) report that the attenuation will be only a factor of 100 if photon propagation is calculated using Monte Carlo simulations, and the average photon energy will be reduced from about 200 keV to about 20 keV. Their argument is summarized as follows.

Scalo and Wheeler point out that, unlike x-ray or UV photons, gamma rays of about 200 keV (the peak GRB gamma energy) interact by Compton scattering, preferentially in the forward direction, with a reduction in photon energy after each scattering interaction. Forward scattering is not unusual and, in fact, is the mechanism by which Jupiter's and Uranus' rings were first imaged. By contrast, conventional shielding calculations assume that scattering is isotropic in nature, a difference that becomes more pronounced with increasing shielding thickness. Their calculations, based on Monte Carlo simulations, indicate that each photon will undergo an average of 40 forward scattering interactions before being absorbed. Based on these simulations, they calculate that about 1% of the incident photon energy will reach the ground, primarily in the form of 20 keV x-ray photons.

Unfortunately, these two approaches provide dose estimates that are at opposite extremes, leaving one with the conclusion that radiation dose at the surface may be either significant or trivial. The rationale presented by Scalo and Wheeler in support of their calculations is compelling, particularly their contention that conventional shielding calculations consider only isotropic scattering and not forward scattering. Determining which of these models is correct is beyond the scope of this paper and will likely require more detailed theoretical analysis supported by experimental measurements. For example, if Scalo and Wheeler's calculations are correct, it should be possible to observe a 20 keV peak in gamma spectra at a distance of several hundred meters from a sufficiently large photon source. Such work has not yet been performed.

More traditional shielding calculations are appropriate once these photons reach the surface of the Earth because the distances and masses transited are much smaller. This attenuation is calculated using the shielding equation:

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

where $\mu$ is the absorption 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 $\mu$ are $cm^2\ g^{-1}$, which were multiplied by the density thickness of the water, about 1 g $cm^{-2}$. The shielding provided by water is of particular interest because life lived almost exclusively in the oceans for nearly 3.5 billion years. The values for attenuation factors and buildup factors came from Schleien (1992) and were checked against values determined using the online version of XCOM (Berger et al. 2000) and the commercial product, MicroShield.[‡]

The values of $\mu$ and $B$ change according to the gamma ray energy and the absorber. Attenuation of photons in water was calculated using the following assumptions:

1. The average energy of photons reaching the Earth's surface is 20 keV (Scalo and Wheeler 2002);
2. About 1% of incident photon energy reaches the Earth's surface (Scalo and Wheeler 2002);
3. The absorption of photons by organisms is identical to the absorption of photons by water; and
4. The photon source can be approximated as an infinite plane.

To calculate radiation dose, it is necessary to determine the actual energy deposited within an organism. Using eqn (2) and a mass absorption coefficient ($\mu_{en/\rho}$) of 0.5503 $cm^2\ g^{-1}$ (Hubbell and Seltzer 1995) for 20 keV photons in water, the exponential term for an organism 10 mm thick is 0.58, so somewhat more than half of the incident energy in the form of 20 keV photons incident upon an organism 10 mm thick will be deposited as radiation dose. The actual value will vary somewhat from this because the photons will not be mono-energetic and because organisms are not composed entirely of water.

Tables 1 and 2 show the calculated radiation doses at sea level and several depths in water and rock from SN and GRBs delivering a radiation dose of $2 \times 10^3$ J $m^{-2}$ to the top of the atmosphere, assuming all energy deposited is in the form of 20 keV photons. This is an event that would occur about every 4.5 million years (My) as a GRB and about every 29 million years as a SN. Scalo and Wheeler (2002) chose a value of $2 \times 10^3$ J $m^{-2}$ because it will deliver a significant sea-level radiation dose, while the mean time between such events is not unreasonably long. This fluence value is used here for similar reasons.

## Radiation dose to organisms in space

There has been occasional 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 (e.g., Hoyle and Wickramasinghe 1981). Calculations of radiation dose in space from GRBs show that any given location in our galaxy will receive a dose of about 200 Gy every million years or so.

[‡] Grove Engineering, 1700 Rockville Pike Suite 525, Rockville, MD 20852.

**Table 1.** Radiation dose rate at sea level from supernovae and gamma ray bursts, using the photon transport simulations described by Scalo and Wheeler (2002). Mean intervals between such events are presented for the three scenarios of galactic evolution discussed in their paper. It is noteworthy that a dose of about 0.2 Gy is likely to be experienced at least every 3 million years, even under the most restrictive scenario.

Gamma ray bursts (assume $E_\gamma \approx 10^{44}$ J)

| Distance (kpc) | Energy fluence in space (J $m^{-2}$) | Sea level dose (Gy) | Mean interval—no galactic evolution ($\times 10^6$ y) | Mean interval—intermediate galactic evolution ($\times 10^6$ y) | Mean interval—strong galactic evolution ($\times 10^6$ y) |
|---|---|---|---|---|---|
| 1 | $8.4 \times 10^5$ | 420 | 2,000 | 3,300 | 7,300 |
| 2 | $2.1 \times 10^5$ | 105 | 490 | 840 | 1,800 |
| 5 | $3.4 \times 10^4$ | 17 | 79 | 130 | 290 |
| 10 | $8.4 \times 10^3$ | 4.20 | 20 | 34 | 73 |
| 20 | $2.1 \times 10^3$ | 1.05 | 4.5 | 7.8 | 24 |
| 50 | $3.3 \times 10^2$ | 0.17 | 0.79 | 1.3 | 2.9 |

Supernovae (assume $E_\gamma \approx 10^{40}$ J)

| Distance (pc) | Energy fluence at earth (J $m^{-2}$) | Approximate sea level dose (Gy) | Mean interval ($\times 10^6$ y) |
|---|---|---|---|
| 1 | 8,400 | 42 | 250,000 |
| 2 | 2,100 | 10 | 31,000 |
| 5 | 340 | 1.7 | 2,000 |
| 10 | 84 | 0.42 | 250 |
| 20 | 21 | 0.1 | 31 |
| 50 | 3.4 | 0.017 | 2.0 |

**Table 2.** Radiation dose at depths in water and rock for an incident energy fluence of 20 J $m^{-2}$ of 20 keV photon radiation at sea level. These doses are representative of those that would be experienced by life on land and in shallow water following a gamma ray burst at a distance of about 20 kpc, occurring with a mean interval of about 4–5 million years.

| Depth (mm) | Dose (water) with buildup (mGy) | Dose (rock) with buildup (mGy) |
|---|---|---|
| 5 | 3.03 | 0.539 |
| 10 | 0.976 | 0.015 |
| 20 | 0.0051 | $1.21 \times 10^{-7}$ |

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, a radiation dose in space of about 151 Gy would yield a radiation dose of 10 Gy at a depth of 0.20 m in water ice and would be expected to occur about every 3.5 My, and a radiation dose of 10 Gy would penetrate to a depth of 0.50 m in water ice about every 211 My. This same dose would penetrate to a depth of about 0.10 m in rocky meteor (assuming a density similar to that of the continental crust) with a mean interval of about 6 My, and to a depth of 0.20 m with a mean interval of about 156 My. These time spans should be compared to the estimated time spent in space by the Allen Hills meteorite of suspected Martian origin; about 16 million years (McKay et al. 1996) simply to travel from Mars to Earth.

These figures include the effects of buildup and were performed using the MicroShield software package. Table 3 summarizes the results of these calculations. They suggest that any stony bodies of less than 0.20 m in diameter or any icy bodies less than 1 m in diameter are unlikely abodes on which living organisms can travel from planet to planet unless their travel time is relatively short. Table 4 summarizes some of this information in a slightly different way, showing the incident fluence of 200 keV photons required to yield an internal radiation dose of 10 Gy at various depths in rock and water ice, the distance at which a GRB could provide this fluence, and the mean interval between such events.

## Mean interval between events

Calculating the typical interval between such events is not simple because the large, short-lived stars that give rise to supernovae and GRBs 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 and the solar system passes through the galactic plane as

**Table 3.** Radiation dose to organisms at several depths in water and rock for an incident energy fluence of 2,000 J $m^{-2}$ of 200 keV photon radiation. These doses would be experienced every few million years by living organisms within a comet or meteor exposed to high levels of gamma radiation from a supernova or a gamma ray burst.

| Depth (mm) | Dose in water with buildup (mGy) | Dose in rock with buildup (mGy) |
|---|---|---|
| 5 | 1,023 | 547 |
| 10 | 834 | 400 |
| 20 | 52.6 | 226 |
| 50 | 38.4 | 15.8 |

**Table 4.** Gamma radiation fluence in space required to give a dose of 10 Gy at various depths in water and rock, and some associated astronomical parameters—first table is in water, second table, in rock. For example, to reach a dose of 10 Gy at a depth of one meter in water ice, a surface radiation dose of 8 million Gy would be required. This would require a GRB to be at a distance of about 100 pc, an event that would take place with a mean interval of nearly 20 billion years, or less than once in the history of the universe to date.

Water/Ice

| Depth (mm) | Dose in space (Gy) | Fluence in space (J $m^{-2}$) | Distance (kpc) | Mean interval ($\times 10^6$ y) |
|---|---|---|---|---|
| 5 | 10.7 | $1.07 \times 10^2$ | 88.5 | 0.25 |
| 10 | 11.5 | $1.15 \times 10^2$ | 85.6 | 0.27 |
| 20 | 13.1 | $1.31 \times 10^2$ | 79.9 | 0.31 |
| 50 | 19.7 | $1.97 \times 10^2$ | 65.2 | 0.46 |
| 100 | 39.0 | $3.90 \times 10^2$ | 46.4 | 0.92 |
| 200 | 151 | $1.52 \times 10^3$ | 23.5 | 3.57 |
| 500 | $8.98 \times 10^3$ | $8.98 \times 10^4$ | 3.06 | 211 |
| 1,000 | $8.1 \times 10^6$ | $8.06 \times 10^7$ | 0.10 | $1.9 \times 10^5$ |

Rock

| Depth (mm) | Dose in space (Gy) | Fluence in space (J $m^{-2}$) | Distance (kpc) | Mean interval ($\times 10^6$ y) |
|---|---|---|---|---|
| 5 | 11.8 | $1.18 \times 10^2$ | 84.4 | 0.28 |
| 10 | 13.8 | $1.38 \times 10^2$ | 77.9 | 0.33 |
| 20 | 19.2 | $1.92 \times 10^2$ | 66.2 | 0.45 |
| 50 | 50.8 | $5.08 \times 10^2$ | 40.6 | 1.19 |
| 100 | 257 | $2.58 \times 10^3$ | 18.0 | 6.07 |
| 200 | $6.65 \times 10^3$ | $6.65 \times 10^4$ | 3.6 | 156 |
| 500 | $1.14 \times 10^8$ | $1.14 \times 10^9$ | 0.0271 | $2.68 \times 10^6$ |
| 1,000 | $1.30 \times 10^{15}$ | $1.30 \times 10^{16}$ | $8.03 \times 10^{-6}$ | $3.06 \times 10^{13}$ |

it orbits the center of the Milky Way. Scalo and Wheeler (2002) have developed a methodology to determine the mean time between GRBs that will deliver a given energy fluence to the solar system. Their work shows that an energy fluence of $2 \times 10^3$ J $m^{-2}$ at the top of the atmosphere (producing a dose of 1 Gy at sea level) will occur about every 5–10 million years. In particular, they note that, during the history of life on earth, it is likely that about 400 events have occurred that would have generated a radiation dose of at least 1 Gy to organisms living at or near the Earth's surface. Table 1 summarizes distance and mean intervals between events for a variety of fluences under three different stellar evolution models.[§] Such models account for the fact that rates of star formation and, consequently, rates of SN and GRBs may have changed over the life of our galaxy, and the mean interval between such events may have been shorter in the past.

The mean interval between SN at different distances was determined by Terry and Tucker (1968) according to the relationship

$$N(R_o, t) = 2 \times 10^{-12} f t R_o^3, \qquad (3)$$

in which $N(R_o,t)$ is the number of SN in a volume of space with a radius of $R_o$ parsecs over a period of $t$ years. The term $f$ is the frequency with which SN occur in our galaxy (about two per century; Binney and Merrifield 1998). Solving this equation for $t$ lets us determine the mean interval between SN at a variety of distances. Assuming $10^{40}$ J of gamma ray energy are released, a SN at a distance of about 40 pc will deliver a radiation dose of approximately 500 J $m^{-2}$ at the top of the earth's atmosphere. The mean interval for such events, using eqn (3), is about 4 My. It must be noted that these mean interval calculations are only valid for distance less than about 600 pc because, beyond that distance, the galaxy can no longer be treated as homogeneous as the galactic disk is about 600 pc in thickness.

## Dose from neutrinos

Most of the energy of SN and an unknown fraction of GRB energy is emitted in the form of neutrinos. One can readily calculate the absorbed dose due to these neutrinos. The average energy of neutrinos released in supernovae explosions is between 5 MeV (Schramm and Brown 1990) and 15 MeV (Sutaria and Ray 1997). Core-collapse SN will produce a neutron star with approximately one solar mass of neutrons (about $10^{57}$ neutrons; Schramm and Brown 1990). A neutrino will be released for each neutron formed, resulting in a neutrino flux of about $10^{57}$ from this type of SN. At a distance of

[§] It is important to stress that the mean intervals are statistical in nature because SN and GRB occur randomly in space and in time. The fact that the Earth is exceedingly unlikely to be very close to a GRB does not mean it will never experience one of these events at short range.

1 pc, these neutrinos will have to fill a sphere with a surface area of $1.19 \times 10^{34}$ m$^2$, giving a neutrino fluence of about $8.4 \times 10^{22}$ neutrinos m$^{-2}$ from the explosion.

At an energy of 5–15 MeV, the primary neutrino interaction mechanism is the $\nu$-nucleus interaction (Cossairt et al. 1997). The dose equivalent per unit fluence, $P(E_v)$ for this interaction is calculated using eqn (4):

$$P(E_v) = 1.6 \times 10^{-4} \sigma_{v-nuclei} T_{ave} \frac{\rho_{nucleus}}{\rho} Q, \qquad (4)$$

where $P(E_v)$ is in units of $\mu$Sv cm$^2$, $T_{ave}$ is the average nucleus recoil energy in MeV (4.5 keV for 5 MeV neutrinos and 40 keV for 15 MeV neutrinos), $Q$ is the quality factor for the ions produced by this process (assumed to be 30), $\rho_{nuclei}$ is $4.60 \times 10^{22}$ cm$^{-3}$, and $\rho$ is the average density of the human body, or about 1.07 g cm$^{-3}$ (Cossairt et al. 1997). The factor of $1.6 \times 10^{-4}$ combines several terms used to convert the results of this equation to the units noted above. The interaction cross section for neutrinos from this interaction ($\sigma_{v\text{-nuclei}}$) is calculated as follows:

$$\sigma_{v-nuclei} = 4.2 \times 10^{-45} N^2 E_v^2 \qquad (5)$$

in units of cm$^2$. In this equation, $E$ is the neutrino energy in MeV and $N$ is the neutron number of the recoiling nucleus. The constant, $4.2 \times 10^{-45}$ combines several constant terms, including unit conversions. Even for oxygen, a moderately heavy element found in tissue, the cross section is $2.42 \times 10^{-40}$ cm$^2$ for 15 MeV neutrinos and $2.69 \times 10^{-41}$ for neutrinos with an energy of 5 MeV.

If all emitted neutrinos have an energy of 5 MeV, the neutrino radiation dose from a SN at a distance of 1 pc is about $1.4 \times 10^{-3}$ $\mu$Sv and, for 15 MeV neutrinos, the dose will be $1.6 \times 10^{-4}$ $\mu$Sv. This level of radiation exposure is trivial and will not be considered further. The biological effects of neutrinos have received some attention (Collar 1996; Cossairt and Marshall 1997; Cossairt et al. 1997), although these dose calculations did not include the expected neutrino energy spectrum used here. While the details of the effects are a matter of speculation, at this low level of dose equivalent, they must be completely insignificant.

### Other sources of radiation exposure from GRBs and SN

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

- High-energy charged particles;
- Ultraviolet light emission from SN and GRBs; and
- Visible light emission.

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 most high-energy charged particles will be electrons or hydrogen or helium nuclei, the majority of radiation dose comes from heavier nuclei such as iron because of their high mass and charge (NCRP 1989). In fact, evidence that SN debris reached Earth within the last 6 million years was recently reported by Knie et al. (1999). However, most charged particles are rapidly deflected by interstellar magnetic fields and they are not expected to produce a very high radiation dose at the earth unless a SN is within a few tens of parsecs (Ellis et al. 1996). Dose from charged particles was not calculated because SN at such close distances occur very infrequently.

Supernovae emit a large flux of ultraviolet light during the initial explosion and subsequently, when the expanding shock wave collides with previously expelled matter. If, as suggested by some recent observations, GRBs are similar to SN, then we can expect that they, too, will emit a large amount of UV radiation. Some of the processes affecting UV emission from SN have been described qualitatively, but a quantitative model has not yet been developed. However, it appears as though many SN exhibit a “UV deficit,” possibly due to absorption by iron and other elements contained in the supernova ejecta. The spectra from GRBs seem to follow a power law that can be extrapolated into the UV, but observational confirmation of this has not yet been forthcoming (Wheeler, personal communication, 2000). The net result is that, while nearby SN may produce a very high UV flux, it is not yet possible to reach any quantitative conclusions about the effects this flux may have had because the UV emission spectra of SN is complex, and the presence of UV absorbers in the early terrestrial atmosphere is not well understood. For now, it must suffice to say that UV radiation was undoubtedly important to early life, but the presence of life today indicates UV was not lethal to all organisms.

There is some evidence that visible light may also cause damage to DNA (Setlow 1999; Woodhead et al. 1999). Because supernova photon spectra peak in the visible band (Wheeler 1990), this form of interaction could lead to significant levels of damage, particularly because the wavelengths thought to be most damaging are precisely those wavelengths that penetrate most deeply into water.

## DISCUSSION

It is immediately obvious that a GRB 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 without the benefit of shielding of some sort. This level of radiation exposure is expected to occur about every one million years on average, and the radiation exposure experienced in the solar system 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 several parsecs and would be anticipated to occur less frequently. Over a distance scale on the order of tens of parsecs, the position of the solar system with respect to spiral arms and the galactic plane is very important, and it spends a relatively small percentage of its time in close proximity to both. It therefore seems unlikely that gamma radiation from nearby supernovae has unduly influenced the radiation environment on Earth. Of the other forms of radiation emitted by SN, most are unlikely to have had a significant impact on terrestrial life during the history of life on earth for a variety of reasons noted above. A potential exception to this is UV radiation and short-wavelength visible light, but their contribution to DNA damage in terrestrial organisms cannot be quantified at this time.

The mean interval of GRBs with the potential to generate a lethal dose of radiation at the surface of the Earth is about once per 80–130 million years (assuming no or moderate changes in stellar formation rates with time), and a dose in excess of 1 Gy would be generated approximately every 5–8 million years. Considering that until relatively recently geologically (about 400 million years ago) life lived almost exclusively in the water, it seems unlikely that nearby GRBs are responsible for mass extinctions due to radiation effects alone. In addition, the short outburst time of GRBs 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 extinctions. In fact, GRB at a distance of about 20 kpc, occurring about every 5–8 million years, would raise radiation levels at the earth's surface to about the mutation doubling dose of 1 Gy. When compared to the mean species survival time of about 5 million years (Raup 1991), it seems that any given species has a reasonably good chance of experiencing, *as a species*, at least one significant dose of radiation from a SN or GRB while extant. 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 deep 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, some of which may date to the earliest life (Mackinodan and James 1990). 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, and some suggest that exposure to any elevated radiation levels is harmful and may caused added risk. Recent work (Karam and Leslie 1999) has shown that life evolved under higher background radiation levels than currently exist, raising the possibility that DNA repair mechanisms may have retained the ability to accurately repair higher levels of radiation-induced DNA damage than exist today. However, background radiation levels from these 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, on the other hand, nearby cosmic events have periodically raised background radiation levels by up to a Gy or more at average intervals of about once per species life-time (and less often, but still significantly elevated levels more frequently), life may be exposed to a relatively constant elevated radiation dose rate when viewed on an evolutionary time scale. This, in turn, may provide an explanation of why DNA damage repair mechanisms would retain the ability to accurately repair higher levels of radiogenic DNA damage than currently exist.

Alternately, it is possible that high-energy galactic events such as these had little impact on early life, which is thought to have lived in the oceans, but had a more significant impact on life after it moved to the land. This might be manifested in qualitative differences of DNA damage repair mechanisms between organisms living in shallow-water or land surface environments vs. those living at depth in the water or soil, a difference that may be testable in the laboratory.

It must be noted that this paper does *not* suggest that elevated levels of radiation at million-year intervals may have directly caused DNA damage repair mechanisms to evolve. Rather, it is possible that the presence of this radiation may have been responsible for *already-existing* repair mechanisms to retain their ability to repair elevated levels of DNA damage, similar to those under which these mechanisms initially evolved. Only a SN or GRB that exploded sufficiently close to cause extinctions could be expected to exert an evolutionary pressure, and such events happen rarely, if at all, in the history of any planet.

## Transport of living organisms through space

There has been much speculation regarding the manner in which life has arisen and, possibly, spread through the galaxy. Recently, this speculation has blossomed into a branch of the growing field of astrobiology. In the past decade, a large body of work, much of it funded by NASA and the National Science Foundation, has reported on various aspects of the origin and dissemination of life on our planet and in our solar system and galaxy. One area of active research is that of "panspermia," the possibility that living organisms may survive extended travel through space, embedded in meteors, comets, or even grains of dust (Mileikowsky et al. 2000).

The size of spaceborne debris varies widely, but, in general, smaller bodies are far more common than larger ones (McDonnell and Gardner 1998; Mileikowsky et al. 2000), and objects on the order of tens of centimeters in size are comparatively rare. 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 bodies and would thus be exposed to very high radiation doses at relatively frequent intervals during their journey through the solar system or through the galaxy. In particular, the dose calculations presented above place serious constraints on the size a host body must be to have a high probability of transporting living organisms through space, and they suggest that dust grains are not a suitable vehicle for the transport of living organisms through the galaxy.

## CONCLUSION

GRBs located anywhere in the galaxy can deliver a lethal radiation dose in space and a significantly elevated dose at the Earth's surface. Dose rates near the mutation doubling dose may occur about once per species lifetime, if we accept the photon transport calculations presented by Scalo and Wheeler (2001). Supernovae can deliver an elevated gamma radiation dose over relatively short distances and long time intervals. However, because of the attenuation provided by the Earth's atmosphere, it is unlikely that the direct gamma ray dose from such events is sufficient in and of itself to have caused the majority of mass extinctions that have been recorded in the geologic record. Obviously, these cosmic events occur and any planets unlucky enough to be nearby may be sterilized, but the probability of one of these events occurring so near Earth is very low. However, even at greater distances, such 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. In fact, we can expect that there will be a sharp increase in background radiation levels at sea level every few million years, providing an occasional challenge to DNA damage repair mechanisms. 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.

*Acknowledgments*—I would like to thank J. Craig Wheeler and John Scalo for their willingness to take the time to share and discuss their work with me. Additional thanks are due John Hubbell, Don Cossairt, Rick Pogge, Kris Sellgren, Audeen Fentiman, and Stephen Leslie for helping me better understand and appreciate various topics about which I knew little and for their helpful comments and suggestions during the preparation and writing of this paper. I also appreciate the helpful comments of three reviewers and an associate editor; because of their comments this is a much better paper than would otherwise be the case.

## REFERENCES

Annis J. An astrophysical explanation for the Great Silence. J British Interplanetary Society 52:19–22; 1999.

Berger M, Hubbell J, Seltzer S, Coursey J, Zucker D. XCOM. Photon Cross Sections Data Base. Online Version 1:2. Gaithersberg, MD: National Institute of Standards and Technology; 2000.

Binney J, Merrifield M. Galactic astronomy. Princeton, NJ: Princeton University Press; 1998.

Collar J. Biological effects of stellar collapse neutrinos. Physical Rev Lett 78:999–1002; 1996.

Cossairt JD, Marshall ET. Comment on biological effects of stellar collapse neutrinos. Physical Rev Lett 78:1394; 1997.

Cossairt JD, Grossman NL, Marshall ET. Assessment of dose equivalent due to neutrinos. Health Phys 73:894–898; 1997.

Ellis J, Fields BD, Schramm DN. Geologic isotope anomalies as signatures of nearby supernovae. Astrophysical J 470:1227; 1996.

Harwit M. Astrophysical concepts. New York: Springer-Verlag; 1982.

Hofflich P, Wheeler J, Khokhlov A. Hard x- and gamma-rays from type Ia Supernovae. Astrophysical J 492:228–245; 1998.

Hoyle F, Wickramasinghe NC, Ponnamperuma C. Comets and the origin of life. London UK: D. Reidel Publishing Co.; 1981.

Hubbell JH, Seltzer, SM. Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest. Gaithersburg, MD: National Institute of Standards and Technology; Report NISTIR 5632; 1995.

Karam PA. Gamma radiation from supernova-produced radionuclides. Radiat Phys Chem; 2002 (in press).

Karam PA, Leslie SA. Calculations of background beta and gamma radiation levels over geologic time. Health Phys 77:662–667; 1999.

Knie K, Korschinek G, Faestermann T, Wallner C, Scholten J, Hillebrandt W. Indication for supernova produced 60Fe activity on Earth. Physical Rev Lett 83:18–21; 1999.

Mackinodan T, James SJ. T cell potentiation by low dose ionizing radiation: Possible mechanisms. Health Phys 59:29–34; 1990.

McDonnell JAM, Gardner DJ. Meteoroid morphology and densities: Decoding satellite impact data. Icarus 133:25–35; 1998.

McKay D, Gibson D, Thomas-Keptra K, Vali H. Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001. Science 273:924–930; 1996.

Mileikowsky C, Cucinotta FA, Wilson JW, Gladman B, Horneck G, Lindegren L, Melosh J, Richman H, Valtonen M, Zheng JQ. Natural transfer of viable microbes in space. Icarus 145:391–427; 2000.

National Council on Radiation Protection and Measurements. Guidance on radiation received in space activities. Bethesda, MD: NCRP; Report 98; 1989.

Raup D. A kill curve for Phanerozoic marine species. Paleobiol 17:37–48; 1991.

Scalo J, Wheeler JC. Astrophysical and biological implications of gamma ray burst properties. Astrophysical J; 2002 (in press).

Schleien B. The health physics and radiological health handbook. Silver Spring, MD: Scinta, Inc.; 1992.

Schramm DN, Brown LE. Neutrinos and particle physics from supernova 1987A. In: Wheeler JC, Piran T, Weinberg S, eds. Supernovae: 1989 Jerusalem Winter School for Theoretical Physics. River Edge, NJ: World Scientific; 1990: 261–288.

Setlow R. Spectral regions contributing to melanoma: a personal view. J Investigative Dermatology Symposium Proceedings 4:46–49; 1999.

Sutaria FK, Ray A. Neutrino spectroscopy of the early phase of nearby supernovae. Physical Rev Lett 79:1599–1602; 1997.
Terry KD, Tucker WH. Biologic effects of supernovae. Science 159:421–423; 1968.
Wheeler JC. Introduction to supernovae. In: Wheeler JC, Piran T, Weinberg S, ed. Jerusalem Winter School for Theoretical Physics: Supernovae. Volume 6. River Edge, NJ: World Scientific; 1990: 1–93.
Wheeler JC. Conference summary: Supernovae and gamma ray bursts. In: Livio M, ed. Space Telescope Science Institute Colloquium on Supernovae and Gamma-Ray Bursts. Baltimore, MD: Space Telescope Science Institute; 2000.
Woodhead A, Setlow R, Tanaka M. Environmental factors in nonmelanoma and melanoma skin cancer. J Epidemiol 9(Supplement):S102–S114; 1999.

■ ■