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Modeling near-Earth Rate of Supernovae and Gamma Ray Bursts

Danylo Sovgut, Ashvini Krishnan, Alex Trauth and Brian D. Fields
University of Illinois at Urbana-Champaign
Department of Astronomy, 1002 W Green St, Urbana, IL 61801, USA

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ABSTRACT

In this paper, we present a model for the rate $\Gamma(r)$ of supernovae and gamma-ray bursts (GRBs) in our Galaxy as function of distance r from Earth. Near-Earth cosmic explosions are of particular interest because the closest ones can threaten the Earth's biosphere, possibly even causing a mass extinction. Local explosion rates are also relevant for mapping out the Galactic Habitable Zone amenable for life in the Milky Way. Even non-catastrophic nearby events can have significant effects, and could be detected by studying remnants, historical records, and especially analysis of isotope ^{60}Fe deposits. Our results are normalized to current Galaxy-wide explosion rates, which should not have changed significantly over the past ~ 1 Gyr of life on Earth in which mass extinction are seen. Our model is axisymmetric and distinguishes between explosions tracing the thin disk (core-collapse supernovae and long GRBs) and the thick disk (Type Ia supernovae and short GRBs) distributions. For the dependence on the galactocentric radius, we compare results following the star distribution with those tracing supernovae remnants. We have also included the effects of star clustering statistically. For all of our models, the core-collapse supernovae and long GRBs occur most frequently, while Type Ia and short GRBs posses much less danger. Rates for core-collapse supernovae and long GRBs at nominal extinction distances of 10 pc and 2000 pc respectively are the following: $\mathcal{R}_{\rm CCSN} = 0.41^{+0.94}_{-0.33}$ Gyr^{-1} and $\mathcal{R}_{\rm LGRB} = 1.37^{+6.47}_{-1.2}$ Gyr^{-1}. We thus confirm that cosmic explosion are a candidate for terrestrial mass extinctions, and compare our result earlier estimates in the literature which came to similar conclusions.

Key words: supernovae – gamma ray bursts – near-Earth rate – mass extinctions

1 INTRODUCTION

The impact of supernovae (SN) on the Solar System, Local Bubble, and Earth's biosphere have been discussed in the literature for many years. (Ruderman 1974; Terry & Tucker 1968; Fields 2004, and references therein). A precise supernovae frequency calculation would benefit astrophysics, astrobiology, and geology. Modeling the frequency of the SN is also important for predicting its first ever observation (Adams, et al. 2013). A new model would also provide insights into how the SN rate inside the Local Bubble, including our Solar System, compares with other regions of the Milky Way. Furthermore, understanding the effects of the SN on Earth could be generalized to its influence on potential life development throughout the galaxy. Effects of the SN could be included in the mapping of habitable zones within our galaxy. Additionally, it has been found that SN is capable of destroying Earth's ozone layer, in turn, significantly increasing the radiation level. This makes them candidates for some of the extinctions and genetic mutations in many species (Ruderman 1974). Possible effects on some species could even lead to vacating niches for the development of intelligent life (Krassovskij & Šklovskij 1958). Modeling the SN rate would also predict probability of the SN threat for our civilization. Non-dangerous cosmic explosions can be insightful in understanding historical records of supernovae events, relevance of these explosions to the development of life, and understanding our own surroundings in the Milky Way. A distance to the SN can be calculated from the density of the ^{60}Fe isotope. While it should not be naturally produced on Earth, multiple geological groups found it in sediments and crusts across the world. Since the deposits of ^{60}Fe could not occur due to cosmic ray influx or meteorites, it could only be attributed to the SN (Schulreich, et al. 2018, and references therein). Its half-life of 2.6 million years allows for a great time resolution. For example, the evidence for the SN event between 1.7 to 2.6 million years ago was found due the influx of ^{60}Fe. It is also worth noting that crust samples have not been significantly affected by bioturbation which is the disturbance of sediment deposits by moving animals. Finally, considering ^{60}Fe evenly spreads out across the Earth and that geological results from multiple groups and samples are in agreement make ^{60}Fe a great candidate for these calculations. However, since its half-life is significantly lower than the age of the mass-extinctions, there could be no geological proof of the cosmic explosion's role of the mass extinctions. Thus, our theoretical models provides quantifying speculations whether a cosmic explosion have had an impact on any of the mass extinctions.

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The first sophisticated calculation of the SN rate appeared in the Fields (2004) where the rate of SN was approximated as $\Gamma = (V_{sphere}/V_{galaxy})N_{sn}$, where V_{sphere} is the sphere with the kill radius, V_{galaxy} is the volume of the galaxy approximated as the disk, and N_{sn} is the galactic supernovae rate. Similar crude calculations have also been made by Terry & Tucker (1968) and Krassovskij & Šklovskij (1958), separately, when speculating that SN could have played a role in mass extinctions. All these calculations, however, failed to account that the SN rate is non-uniform in our galaxy. We have found a significant difference between their calculations and our improved model, especially for the GRBs. Although GRBs have previously not have been given as much attention in the literature as the supernovae, we have found that Long GRBs to have greater kill rates than the supernovae.

2 METHODS

2.1 Explosion Rate Density

The rate for a given cosmic explosion is the number of explosions per unit time and volume:

$$q_i(R, z) = \frac{dN_i}{dV\ dt} \tag{1}$$

where (R, z) are the usual galactocentric cylindrical coordinates, and subscript i denotes the type of explosion. If we integrate over the volume of the whole galaxy, we get back the galactic rate for a given type of explosion: $\int q_i(R, z) dV = \mathcal{R}_\mathrm{i}$. We implicitly assume axisymmetry and ignore any dependence on the galactocentric azimuth ϕ. Thus we ignore effects of a Galactic bar, or spiral arms; see Discussion for consequences of relaxing this assumption. We have used two models to account for a non-uniform distribution of supernovae in the Milky Way. In each model, we differentiate between thin disk population for LGRB and CCSN and thick disk population for SGRB and Type Ia supernovae. It does not change the functions but only changes inputs for scale height and radius as shown below:

	Scale Height	Scale Radius
Thick Disk	800 pc	2400 pc
Thin Disk	95 pc	2900 pc

a)*TRILEGAL Model* from Girardi, et al. (2005) follows galactic star distribution. We have also assumed that SN and GRB follow this distribution. Adams, et al. (2013) used it to model the distribution of supernovae for predicting future SN events.

$$q(R, z)_{\mathrm{Trilegal}} = \frac{\mathcal{R}_{\mathrm{SN}}}{4\pi\ R_0 H_0^2}\ e^{-R/R_0}\ e^{-|z|/h}. \tag{2}$$

b) *Green Model* describes the distribution of supernovae remnants in our galaxy, from which we infer the distribution of the supernovae. The catalogue is based on the 294 entries of which 20 remnants could not be detected with any confidence because of the low flux density (Green 2015). The catalogue is also not homogeneous since remnants were combined from radio and various other observational parameters. Green also acknowledges biases associated with identifying fainter samples (Green 2015). Inferring supernovae distribution from this catalogue also has its limitations, mainly remnants closer to the turbulent galactic center will live shorter lives so this model underestimates the number of supernovae in the galactic center. Furthermore, the Green distribution avoids the center of the galaxy. However, Green's catalogue is still useful for deriving the supernovae rate:

$$q(R, z)_{\mathrm{Green}} = \frac{\mathcal{R}_{\mathrm{SN}}}{4\pi\,\Gamma(\alpha+2) R_0^2 h} \left(\frac{R}{R_0}\right)^{\alpha}\ e^{-R/R_0}\ e^{-|z|/h}. \tag{3}$$

2.2 Local Rates of Cosmic Explosions

Our goal is to calculate the local rate $\Gamma(r)$ of explosions within a spherical volume of radius r. The local rate has units of frequency $[\Gamma] = [\mathrm{events/yr}]$, and depends on the observer's location (R, z) in the Galaxy. For the general case, a rate inside the spherical volume $V(a)$, with a radius a, *centered on the observer*:

$$\Gamma(< a) = \int_{V(a)} q(\vec{x})\ dV \tag{4}$$

The rate density $q(\vec{x})$ is mostly not uniform over this volume. Thus, our model can be used to calculate the local explosion rate inside any volume or for any observer. However, our focus will be on the local rate of explosions at the Earth's location, though we will comment on how this changes for other observers.

$$\Gamma(a) = \int_0^{2\pi} d\ell \int_{-\pi/2}^{+\pi/2} \cos(b)\ db \int_0^a r^2\ q(R, z)\ dr \tag{5}$$

This uses observer-centered Galactic coordinates, with radius r centered on the observer, and the usual Galactic longitude and latitude (ℓ, b), providing inputs for $R(r, \ell, b)$ and $z(r, \ell, b)$. Note that this integral does not have a simple analytic solution, thus, we evaluate it numerically. However, some simplifying approximations could be of interest.

a)*Uniform approximation* assumes that the rate in the given spherical volume with radius a is uniform. The equations (1) and (2) are simply multiplied by the volume of the sphere. This is a good approximation when calculating near-Earth supernovae (SN) rate because the SN kill distance is only 10 pc and distribution does not vary significantly in that volume. However, this model is very primitive and breaks for larger distances such as kill distances of SGRBs of 91.42 pc and LGRB of 2044 pc.

$$\Gamma(a; R, z) = q(R, z)\frac{4\pi a^3}{3} \tag{6}$$

b)*Exponentially Varying Height* approximates supernovae distribution as constant in the radial direction while height (z) varies exponentially inside a spherical volume. We can ignore the radial component because the radius of interest is much less than the scale radius of the Trilgal model $(H_0, R_0) = (95\ \mathrm{pc}, 2.7\ \mathrm{kpc})$. Although this approximation breaks for distances close or greater than 2.7 kpc, it is still a very precise approximation for the SN and GRBs kill distances .

$$\Gamma(a; R, z) = 4\pi h^2\ q_0\ e^{-R/R_0}\ e^{-|z|/h} \left[a\cosh(\frac{a}{h}) - h\sinh(\frac{a}{h})\right] \tag{7}$$

2.3 Solar Location

Galaxy mid-plane height of the sun $z_\odot$ = 24 pc and distance from the center of the galaxy $R_\odot$ = 8.7 pc (Adams, et al. 2013); On the scale of Gyr, the solar height z changes quite significantly which will affect the explosion rate. The rate at $z = 0$ will be the greatest, because the solar system is in the plane of the galaxy. However, it also spends the least amount of time in the plane of the galaxy so instead of picking $z = 0$, we calculate the average solar height above the mid-plane. The solar height could be an important factor in explaining some of the mass extinctions (Bahcall & Bahcall 1985, and references therein).

We can define the probability of the sun to be at the location $P(z)$ and the time above the disk as $T = P/2$. We then find that $\frac{dP}{dz} = \frac{1}{T}\frac{1}{v_z}$. Since the motion of the sun is approximately sinusoidal, we can write $z(t) = z_{\max}\ \sin(\omega t)$, which gives us $v(z) = \omega z_{\max}\ \cos(\omega t) = \omega\ \sqrt{z_{\max}^2 - z^2}$. From here, we derive the mean value of z for one positive or negative excursion as:

$$\langle |z| \rangle = 2\int_0^{z_{\max}} z\ \frac{dP}{dz}dz = \frac{2}{\pi}z_{\max}\int_0^1 \frac{u}{\sqrt{1-u^2}}du = \frac{2}{\pi}z_{\max} \quad (8)$$

Bahcall & Bahcall (1985) finds that $z_{\max} \in (49, 93)$ pc, and we adopt $z_{\max} = 71$ pc which is the median in that interval. Thus, our baseline calculation will use a solar height of $\langle |z| \rangle = 45.2$pc. We will see that a non-zero height above the mid-plane decreases the threat and we will further explore how this parameter changes the results quantitatively.

2.4 Clustering

Most stars are born in clusters, including SN progenitors. SN global spatial distribution remains the same when including effects of clustering. Then, the cluster bursts would occur at a rate:

$$\Gamma(a; R, z)_{cluster} = \Gamma(a; R, z)\frac{1}{n} \quad (9)$$

n is the number of stars in the cluster. Time between supernovae explosions withing the cluster is approximately 10 million years. This interval is negligible in the context of near-Earth rate. Notice, that clustering does not influence the average expected rate of cosmic explosions since when the cluster of n supernovae would explode, they would all go off at once and an average rate would stay the same: $\Gamma(a; R, z) \cdot \frac{1}{n} \cdot n$. However, the mean time between explosions would increase by n due to clustering. Average number of SN in clusters n - 10.

3 DATA

3.1 Kill Distance

Kill Distance a is defined as the distance at which an explosion would deplete 30% of the ozone layer, increasing the radiation level enough to cause a mass extinctions (Fields 2004). Here, we provide kill distances for each explosion type:
$d_{\mathrm{killSN}} = 8 - 10$ pc, but we favor 10 pc as the upper limit; (Fields 2004)
We have derived kill radius for SGRB and LGRB from the kill fluences and kill energies in Melott & Thomas (2011)
$d_{\mathrm{killSGRB}} = 91.42$ pc, $d_{\mathrm{killLGRB}} = 2044$ pc;

2. Kill energies from Melott & Thomas (2011)
$E_{\mathrm{sn}} = 1.20 \cdot 10^{40}$ J, $E_{\mathrm{sgrb}} = 10^{43}$ J, $E_{\mathrm{lgrb}} = 5 \cdot 10^{45}$ J

3.2 Explosion Rates

We took explosion rates for CCSN $\mathcal{R}_{\mathrm{CCSN}}$ and Type Ia supernovae $\mathcal{R}_{\mathrm{IaSN}}$ directly from the Adams, et al. (2013). Since there was no

	Explosion rate (yr^{-1})	Source
CCSN	$3.2^{+7.3}_{-2.6}\ 10^{-2}$	(Adams, et al. 2013)
Type Ia	$1.4^{+1.4}_{-0.8}\ 10^{-2}$	(Adams, et al. 2013)
SGRB	$3.14^{+98.86}_{-2.989}\ 10^{-6}$	derived from Fong, et al. (2015)
LGRB	$1.22^{+5.73}_{-1.061}\ 10^{-7}$	derived from Lien, et al. (2015)

result for galactic LGRB and SGRB rate to the best of our knowledge, we have derived it using the fact that LGRB and SGRB are related to the CCSN. Therefore, we could use the rate in the local galaxies to infer the rate in our own as follows:

$$\mathcal{R}_{\mathrm{GRB}} = \mathcal{R}_{\mathrm{CCSN}}\frac{\mathcal{R}_{\mathrm{localGRB}}}{\mathcal{R}_{\mathrm{localCCSN}}} \quad (10)$$

We have adopted local galactic LGRB rates from Lien, et al. (2015) of $0.42^{+0.09}_{-0.04}\ \frac{1}{\mathrm{Gpc^3 yr}}$ and local galactic SGRB rate from Fong, et al. (2015) of $10.8^{+63.2}_{-7.2}\ \frac{1}{\mathrm{Gpc^3 yr}}$. We plugged these values into eq. 10 and derived following galactic GRB rates:
$\mathcal{R}_{\mathrm{SGRB}} = 3.14^{+98.86}_{-2.989}\ 10^{-6}\ \frac{1}{\mathrm{yr}}$
$\mathcal{R}_{\mathrm{LGRB}} = 1.22^{+5.73}_{-1.061}\ 10^{-7}\ \frac{1}{\mathrm{yr}}$
This is beam uncorrected galactic GRB rate. We are only interested in beam uncorrected rates because only GRBs that are pointed directly at us pose a threat to the Earth's biosphere.

3.3 Model Parameters

Scale Height and scale radius are adopted from Adams, et al. (2013) for both thick and thin disk approximations for the Trilegal model.
We use thin disk approximation for modeling LGRB and CCSN: $H_{thin} = 95$ pc; $R_{thin} = 2.9$ kpc.
A thick scale height and radius are used for modeling SGRB and Type Ia SN: $H_{thick} = 800$pc and $R_{thick} = 2.4$ kpc

Green (2015) defines two terms a and b to account for supernova remnant selection bias. He proposes multiple values for these parameters, but favors $a = 1.09$ and $b = 3.87$ (Green 2015);
We ignore the uncertainties in the scale height and radius, location of the sun, and kill radius, as well as uncertainty in other quantities. Our calculations showed that uncertainty in galactic explosion rates significantly dominate over all the other sources of error in our final result for SGRB, LGRB, and SN local rates.

4 RESULTS

The table below summarizes mean times, which are inverse to the solution of the rate equation 5 . Each of the mean time was evaluated at the respective kill distance for each type of explosion. It is worth noting that both Trilegal and Green model agree closely with each other. These mean times are for individual explosions and to get the cluster mean time, the answer would have to be multiplied by n, number of the supernovae in a cluster.

While analyzing these numbers, it is worth considering timescales of Earth's age of ≈ 4.5 billion years and life on Earth of ≈ 3.5 billion years. This means that at least one or two near-Earth CCSN or LGRB has occurred with the biological life on Earth. A near-Earth SGRB or Type Ia would not never been expected to occur over the age of the Earth. However, all the five major extinctions occurred during the period of ≈ 500 million years. It becomes much more speculative

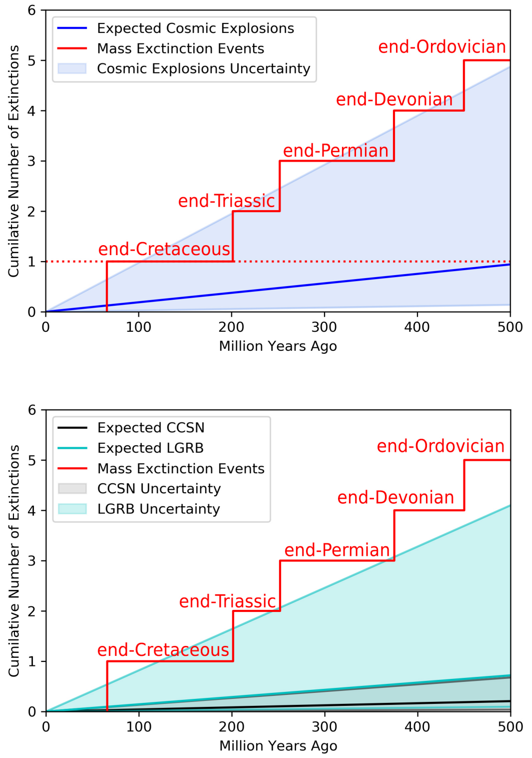

Figure 1. Top panel: the total expected mass extinction rate is shown in the solid blue line. The error for the rate of the mass extinctions is shown in shaded blue area. All extinction events is show in each panel with their respective names labeled. Most mass extinction events are within the error for the expected cosmic explosion rate and at least one mass extinction event aligns with the expected cosmic explosion rate. Bottom panel: most threatening cosmic explosions are LGRB and CCSN. The SGRB and Type Ia supernovae are not threatening so that they would be seen as almost zero on this plot. The LGRB is the most dangerous explosion, but still comparable to the CCSN. Error for the CCSN is displayed in black and it is within the error for the LGRB.

Explosion Type	Mean Time (Gyr) Trilegal model	Mean Time (Gyr) Green model
CCSN	$2.41^{+10.48}_{-1.68}$	$1.72^{+7.48}_{-1.2}$
Type Ia	$39.49^{+52}_{-19.89}$	$22.04^{+29.02}_{-11.1}$
SGRBs	$22.84^{+452.3}_{-22.13}$	$12.74^{+252.36}_{-12.35}$
LGRBs	$0.72^{+4.83}_{-0.6}$	$0.5^{+3.32}_{-0.41}$

whether a cosmic explosion has contributed to any of these major extinctions since the mean time for each explosion is larger than the timescale for mass extinctions. Given a large uncertainty associated with each explosion, it is still likely that at least one of the explosion types, such as LGRB or CCSN, could be responsible for one of the mass extinctions. The plot 2 was calculated using Trilegal model, and it illustrates the rate inside a sphere with the radius r. The dash line signifies the kill rate. In the middle of the galaxy the density becomes more homogeneous and the rate does not change as significantly, which is why the line flattens.
This plot would resemble similar features for the Green model except it would have different scales on the y-axis. The same pattern occurs with the GRBs in the fig 3 since the only differences from the supernovae are the rate and kill radius for each explosion.

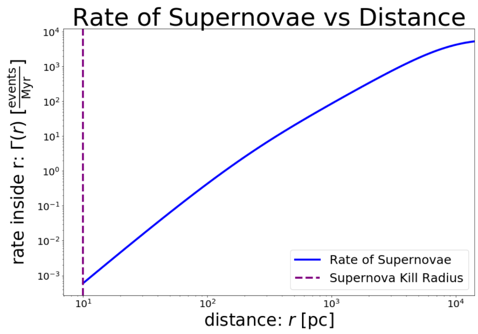

Figure 2. Rate of explosions in the sphere with a radius r from the Earth. Core collapse supernova and GRB event distribution assumed to follow the thin disk. Type Ia supernovae are assumed to trace the thick disk. Vertical line signifies a kill radius, where the cosmic explosion would significantly damage Earth's ozone layer. Top panel: Supernovae Rate, bottom panel: Soft and Long GRBs rate.

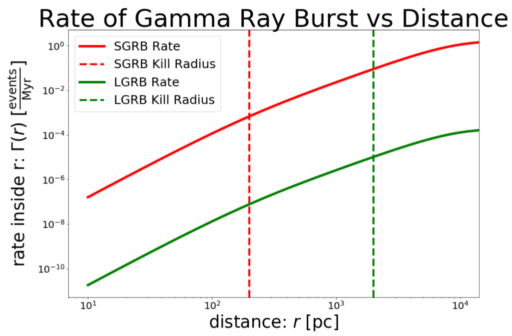

Figure 3. GRBs Rate

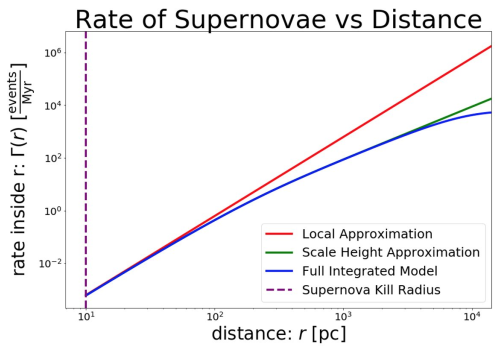

Figure 4. Comparison of the supernovae rate produced by the different approximation models. A Local Approximation assumes that in the sphere with the kill radius r, rate does not vary; Exponentially Varying Height that the supernovae rate varies in only the height z, and Full Integration that the rate varies inside the sphere both in height and radially.

In figure 4, it is evident how the uniform model is valid for close distances such as the supernovae kill radius. However, with the larger radius, variations of rates inside a sphere become more significant and uniform model becomes less accurate and lines diverge. Thus, solving the integral becomes important for calculating SGRB and LGRB rates, since their kill distances of 91.42 pc and 2044 pc are way greater than those of the supernova's 10 pc. Interestingly, the exponentially varying height approximation is very close to the complete calculation. We have previously discussed the significance of the solar height z in 2.3. We present results for the two most extreme choices of z: $z = 0$ pc, when solar system is in the plane of the galaxy and $z = 93$ pc when it is furthest away from the plane of the galaxy.

	$\mathcal{R}_{\rm CCSN}$	$\mathcal{R}_{\rm LGRB}$
z=0	$6.39^{+14.59}_{-5.2}$	$1.38^{+6.5}_{-1.2}$
$z = 93$ pc	$3.57^{+8.14}_{-2.9}$	$1.37^{+6.45}_{-1.19}$

The variations in solar height is not significant for explosions with great kill distances such as LGRB and SGRB, but could be important up to a factor of 2 for Type Ia supernovae and CCSN. We have also investigated how different solar radius affect the rate and found that rate does not influence the rates significantly. We have tried the range of 300 pc for the solar height, such as$R_{\rm sun} = 9$ kpc and $R_{\rm sun} = 8.7$ kpc. We found no difference in the cosmic explosion rate.

5 DISCUSSION

Explosion Gyr^{-1}	SN	GRB
Krassovskij & Šklovskij (1958)	3.33	-
Fields (2004)	3.7	-
Melott & Thomas (2011)	1-2	4
Our Result	$0.43^{+0.96}_{-0.35}$	$1.42^{+7.84}_{-1.24}$

In this table, we present results of previous studies that have mentioned rates of cosmic explosions (Krassovskij & Šklovskij 1958),(Fields 2004),(Melott & Thomas 2011). Since most studies do not differentiate between types of supernovae and GRB, we have combined all the cosmic explosions into two categories. From the table, we can see that our rate estimate is significantly lower than those of the previous authors. It is not surprising, since previous studies treated rate explosions as being uniform across the galaxy. Our study, however, accounts for the fact that there are less explosions in the solar neighborhood because the solar system is located in the outskirts of the galaxy. We have also improved previous rate estimates by breaking down supernovae and GRBs into respective categories.

Firstly, we have assumed axisymmetry, but in the future studies one would wish to account for the effect of spiral arms on the explosion rate. Spiral arms increase the star formation rate, therefore, increasing the explosion rate. On the timescales of Gyr the effect averages and could be ignored. Moreover, spiral arms have non-symmetric complex features and patterns. Accounting for these features is beyond the scope of this study.

One of our assumptions was also that the galactic explosion rate does not change significantly in our galaxy for timescales of Gyr.

We have incorporated some variations with how the sun's height above the galactic mid-plane z influences the cosmic explosion rate. However, over timescales of Gyr, the explosion rate and star formation rate would probably not change significantly in our galaxy.

Furthermore, the overall pattern of galactic explosions would remain the same - the galactic center would experience high rates of explosions and the outer regions would be less violent. The greatest feasible improvement to this study would be decreasing the uncertainty in the galactic explosion rates. For GRBs, this would rely on better estimates of local galactic explosion rates from which we could develop a more sophisticated model for estimating rates in the Milky Way.

6 CONCLUSIONS

We have significantly improved the estimates for explosion rates from the previous studies (Fields 2004; Ruderman 1974). We have demonstrated that the cosmic explosion rate distribution is a significant factor in estimating rates. It turned out to be the most important for SGRB since the rate varies greatly in the volume of its kill distance of $200pc$. We were able to show that SGRB pose a comparable threat to the supernovae explosion. We also showed that at least one killer cosmic explosion (either SGRB or SN) has occurred over the lifetime of the Earth. Killer LGRBs practically never happen. Cosmic explosions may have caused or contributed to one of the major extinctions because the rate of mass extinctions overlaps with the cosmic explosion rate. We simply suggest it as a possibility and more work has to be done to prove this connection. Cosmic explosions definitely are not a threat to the human civilizations. As we have shown, they do not happen on the timescale of human existence. Furthermore, this study can have implications beyond the effects of explosions on Earth's biosphere. With our model, it is possible to calculate explosion rates in any location or volume of the galaxy. This could tie into the discussion of Galactic Habitable Zone. In some regions of our galaxy, the explosions would go off too frequently, in turn, increasing the radiation prohibiting life from development (unless organisms manage to adopt to high levels of radiation).

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