Off-Axis Gamma Ray Burst Contribution to the Diffuse Gamma Ray Background in the 100-600 keV Range

By
Isaac Hodges

A THESIS

submitted to

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(Honors Associate)

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Abstract approved:

Davide Lazzati

Gamma ray bursts (GRBs) are short, intense pulses of gamma rays that emit radiation in a narrow beam. Unless the beam is oriented towards the observer, it is often difficult to resolve the bursts against the diffuse gamma ray background (DGRB). The DGRB is a measured source of gamma rays that is known to come from a variety of different sources. Between photon energies of approximately $200 keV$ and $600 keV$, it is not fully known what sources contribute to the observed gamma rays. In this thesis we use a blob-cone model to simulate a population of unresolved gamma ray bursts in this energy region. We find that using a simplified set of burst parameters allows off-axis gamma ray bursts to account for only $1-7\%$ of the observed gamma ray background.

Key Words: Astrophysics, Gamma Ray Burst, Diffuse Gamma Ray Background

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I understand that my project will become part of the permanent collection of Oregon State University Honors College. My signature below authorizes release of my project to any reader upon request.

Isaac Hodges, Author

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1 Introduction

1.1 Background

1.1.1 Definition of gamma ray bursts

Gamma ray bursts (GRBs) are intense pulses of gamma rays that can last anywhere from a few milliseconds to hundreds of seconds. They are typically observed from distant galaxies in all directions, suggesting that they are caused by conditions found in the earliest galaxies [7]. GRBs fall into two broad classifications: long GRBs and short GRBs. The distinction between these two forms happens at around a burst duration of 2 seconds [2]. GRBs of all types are usually followed by a afterglow which consists of a longer emittance period in the x-ray, optical, and radio spectral ranges [7]. While invisible to the naked eye, GRBs are the brightest events in the sky with a luminosity of around $10^{51} erg/s$ [7]. Currently, very little is known about what drives a gamma ray burst. Some prominent theories include: black hole accretion, pulsars, stellar collapse, and merging neutron stars or black holes [7].

One of the main features that defines a gamma ray burst is its jet. A jet is a stream of matter moving at a highly relativistic velocity. It is generally accepted that the GRB event happens when the kinetic energy of the relativistic flow of matter is dissipated [7]. The dissipation of the kinetic energy can be caused either from surrounding stellar matter or from internal fluctuations within the jet itself. These two types of fluctuations are called "external shocks" and "internal shocks" respectively.

1.1.2 History of GRB studies

The presence of the afterglow is important because it provides a point to determine the location of the burst [7]. In the late 1990s, GRBs were observed to occur randomly but at cosmological distances. This ruled out the possibility that what was being observed was local phenomena like soft gamma ray repeaters [2]. By determining the approximate location of GRB events and their energetic requirements, it is possible to begin making guesses as to what drives GRBs. Long GRBs are typically seen to occur in star forming regions of their host galaxies [7] which leads to suspect that long GRBs are associated with massive stars. Additionally, there is evidence that the rate of long GRBs is proportional to the rate of star formation in galaxies [7]. In contrast, short GRBs are observed to originate from older stellar regions [2]. The fact that short GRBs originate from old stellar regions suggests that they are the result of binary mergers of older stellar objects such as black holes or neutron stars.

1.1.3 Gamma Ray Background

The extragalactic diffuse gamma ray background (DGRB) is the name given to the gamma rays detected after subtracting the galactic disk foreground emission [4]. What remains is a spectrum of diffuse nearly isotropic gamma rays emitted from a number of different sources thought to be primarily of extragalactic origin [3]. These sources include but are not limited to: blazars, misaligned active galactic nuclei, star forming galaxies and millisecond pulsars. These sources are often too dim to be resolved on their own so it is interpreted that the DGRB is the result of the cumulative emission of many sources [3]. Different sources contribute to different parts of the spectral flux seen by telescopes. For example, the measurements performed by the Fermi large area telescope in the $100 MeV$ - $820 GeV$ range revealed that the DGRB in that range is largely composed of blazars [4] [5].

1.2 On-axis vs off-axis observed fluxes of GRBs

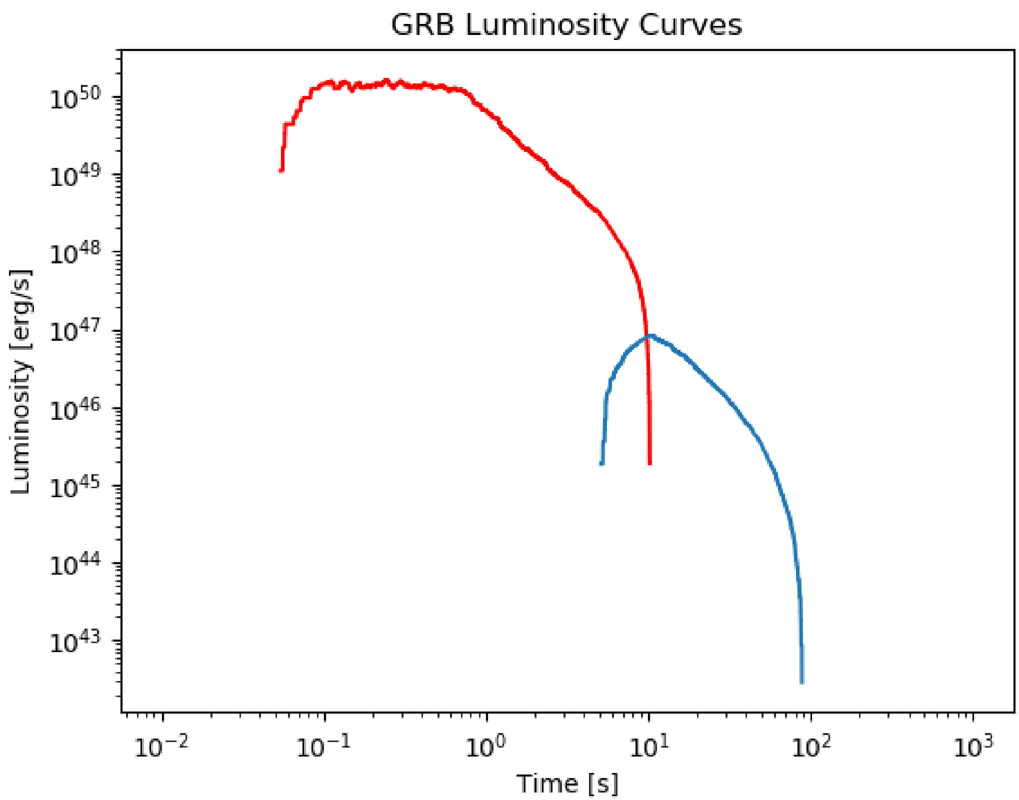

Figure 1: Comparison of simulated luminosity curves of a single burst observed at two different angles. The red curve is the luminosity curve of the burst from looking directly into the jet and the blue curve is the luminosity from looking at the jet form a 20° angle.

Since GRBs are so narrowly beamed, it is often difficult to resolve them among the diffuse gamma ray background unless the observation angle relative to the axis of the jet is less than or equal to the opening angle of the jet. An on-axis observation of a GRB will appear to have a much higher intensity at higher photon energy than an off-axis observation. The beaming is a result of the matter stream moving relativistically. To an observer in a reference frame other than the matter stream, most of the emitted radiation appears to be beamed along the axis of the jet. This beaming effect is what causes on-axis observations of the GRB appear to be so bright while off-axis observations are relatively dim. Additionally, blobs moving at an angle to the observer will appear to be luminous for longer since the distance between the observer and the blob decreases at a slower rate. Figure 1 demonstrates both the relativistic beaming and time delay by comparing the light curves of the same burst but observed at different angles.

1.3 Motivation and Objective

As discussed in section 1.1.3, the observed flux of the DGRB is made up of different sources depending on the range observed. For low energies ($< 300KeV$), the observed flux can be explained by active galactic nuclei (AGNs) and Seyfert galaxies [10] while at higher energies ($> 30MeV$) the observed flux is mostly explained by blazars [4] [5]. The remainder of the spectrum however, is still largely unexplained. Attempts have been made to explain the observed flux in the low MeV range with type 1a supernovae (SN1a), but the most recent estimations say that SN1a explosions only account for $20\% - 50\%$ of the observed flux [5]. Additionally, the flux contribution of SN1as falls off quickly at photon energies lower than $500keV$. This falloff leaves a gap in known sources that can contribute to the DGRB from about $200keV$ to $600keV$. In this thesis, we use a blob-cone model of GRBs to simulate observed gamma ray flux from unresolved gamma ray bursts in the energy region of $100 - 600keV$ as a possible explanation for the observed flux in this energy band.

2 Methods

2.1 Gamma Ray Burst Model

In our code, we adopt a "blob cone" model of gamma ray bursts in which blobs, representing relativistic matter streams, are flung outward at relativistic speed characterized by $\beta = \frac{v}{c}$ in a cone from a central location as depicted in Figure 2. Between the radial distances R_1 and R_2, the blobs emit radiation in a blackbody spectrum with intensity as a function of frequency (ν) defined by Planck's law in equation 1.

$$l(\nu) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{kT}} - 1} \tag{1}$$

where h, k, and c are Planck's constant, Boltzman's constant, and the speed of light respectively and T is the co-moving temperature of the fireball. The amount of energy each blob has to emit is normalized by setting the total fireball energy and dividing by the number of blobs.

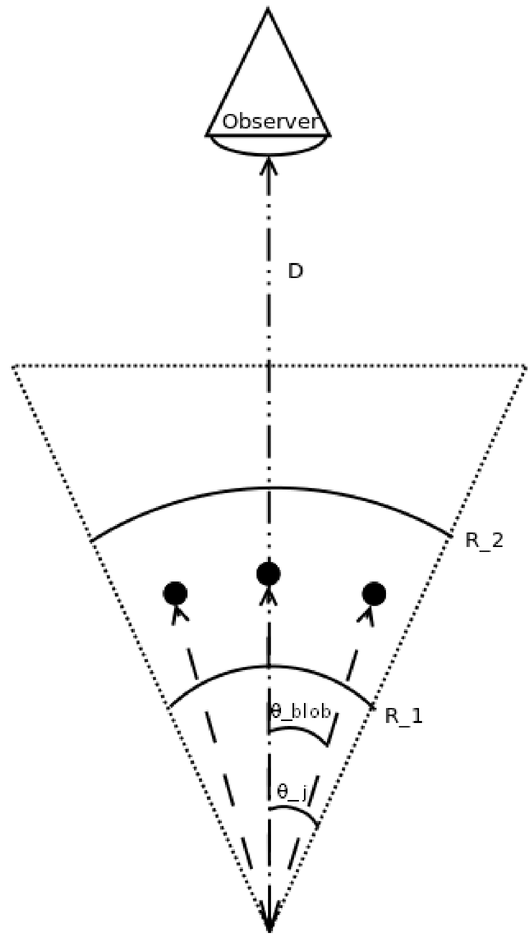

Figure 2: 2D Representation of "light emitting blob cone". The number of blobs used is variable and defines resolution of the simulation. More blobs means a more accurate light curve.

In the blob cone model, the blobs must be distributed so that they are representative of a GRB jet. We associate each blob with a unit vector defined in spherical coordinates with the z-axis aligned along the center of the jet. Blobs are distributed randomly in the whole region azimuthal direction and are distributed between 0 and the jet opening angle θ_j in the altitudinal direction. In the altitudinal direction, blobs are distributed by choosing a random number x between 0 and 1 and solving for θ_{blob} such that

$$x = \frac{\cos\theta_j - \cos\theta_{blob}}{1 - \cos\theta_{blob}} \tag{2}$$

By choosing θ_{blob} in this manner, we ensure that blobs are spread out evenly throughout the cone.

2.2 Observation Model

Since the blobs are moving relativistically, we take into account how the Doppler affects the observed intensity. We define the observation angle dependent Doppler factor for an approaching source.

$$\delta = \frac{\nu_s}{\nu_o} = \frac{1}{\gamma(1 - \beta \cos\theta_o)} \tag{3}$$

where $\frac{\nu_o}{\nu_s}$ is the ratio between the source frequency and the observed frequency, θ_o is the angle of observation and γ is the Lorentz factor $\frac{1}{\gamma} = \sqrt{1 - \beta^2}$.

In addition to the angular dependence of the Doppler effect, there is angular dependence in the first received photon and the last received photon. In the observer reference frame, the time of arrival for a photon emitted from a blob at distance R from its point of origin is

$$t_{us} = \frac{R}{\beta c} - \frac{R\cos\theta_o}{c} \tag{4}$$

We assume $\beta \approx 1$ so we can approximate t_{us} to be

$$t_{us} \approx \frac{R}{c}(1 - \beta\cos\theta_o) \tag{5}$$

Observed intensity of radiation from the GRB calculated on a blob-by-blob basis then results are combined into an overall light curve. For each GRB, an orientation is space is chosen at random by giving the observer a random unit vector. For each blob, the spectral intensity defined by the blackbody spectrum is then integrated over a frequency bandwidth defined by ν_{min} and ν_{max}.

$$L = C\int_{\nu_{min}}^{\nu_{max}} \delta^3 l(\nu')d\nu' \tag{6}$$

where ν' is the frequency in the observer reference frame, δ^3 is the relativistic beaming factor from δ as defined in equation 3. C is a constant of normalization calculated by defining the energy emitted by a blob between R_1 and R_2 to be a fraction of the total energy available to each blob.

$$C = \frac{15\ c^3\ h^3\ \beta\ \epsilon E_i}{8\pi^5 \Delta R\ k^4\ T^4} \tag{7}$$

With ϵ being the efficiency factor, assumed to be $\epsilon = 0.1$. ΔR is the distance between which the blobs emit radiation and E_i is the energy associated with each blob. β is the ratio between the blob's velocity ans the speed of light, assumed to be $\beta = 0.9999$.

The observed flux for a GRB at luminosity distance $d_L(z)$ is then calculated by the inverse square law

$$f = \frac{L}{4\pi d_L(z)^2} \tag{8}$$

The observed flux is then averaged over the course of 1 day. Over the course of 1 year, 2500 bursts are simulated and bursts simulated on the same day are added together. Then, the average flux over the year is calculated which defines the average intensity.

$$f = \int I_\nu \cos\theta d\Omega \tag{9}$$

2.3 GRB Population

It is believed that the rate of GRBs is connected to the rate of star formation in galaxies at cosmological distances [7], however it is still not clear what the ratio of the GRB rate to the star formation rate might be. Therefore, we adopt a simple model in which the average rate of GRBs is 10^{-3} times the rate of star formation. We adopt a model from Porciani *et al.* that estimates higher rates of star formation per co-moving volume during the early universe [8].

$$R_{SF}(z) = 0.2H_0 \frac{\exp(3.05z - 0.4)}{\exp(2.93z) + 15} \tag{10}$$

in units of $Solar\ Mass\ yr^{-1}\ Mpc^{-3}$ where H_0 is Hubble's constant. The observed rate of bursts at redshift z is

$$\frac{dN}{dt\ dz} = \frac{dV(z)}{dz} \frac{R_{GRB}(z)}{1+z} \tag{11}$$

$\frac{dV}{dz}$ is the co-moving volume element [8].

$$\frac{dV}{dz} = \frac{c}{H_0} \frac{\Delta\Omega_s d_L(z)^2}{(1+z)^2[\Omega_M(1_z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda]^{1/2}} \tag{12}$$

where $\Delta\Omega_s$ is the solid angle made by the sky survey and Ω_K is the curvature contributed by the density parameters Ω_M and Ω_Λ.

In order to generate a distribution of redshifts for our simulation, we first generate a list of random redshifts (Z_{rand}) between 0 and 10. A second list of GRB rates (N_{rand}) is then generated between 0 and the peak rate given by $\frac{dN}{dt\ dz}(z)$ calculated from our list of random redshifts. For each element i of Z_{rand} we check to see if $\frac{dN}{dt\ dz}(Z_{rand}[i]) \geq N_{rand}[i]$. If true, then we save $Z_{rand}[i]$ to another list, otherwise the value is thrown out.

For each GRB simulated, the observation angle is randomized between 0 and 90 degrees. Since GRBs observed on-axis have very high intensity [9], any GRB with $\theta_{obs} < \theta_j + 2^o$ is assumed to be resolved among the gamma ray background and is not used as part of our data.

2.4 Simulation Parameters

For simplicity, the physical parameters that define the geometry and emitted spectrum of bursts were kept constant throughout simulation, the values of which are referenced in Table 1.

Table 1: Physical properties of bursts are chosen to be approximate values of what might be expected from a typical GRB.

Parameter	**Value**	**Units**
β	0.9999	
R_1	1×10^{13}	cm
R_2	2×10^{13}	cm
N_{blobs}	1000	
E_{burst}	10^{53}	ergs
ϵ	0.1	
T	10^7	K
θ_j	10	deg

For the distribution of bursts we use a flat ΛCDM model with $H_0 = 65 km\ s^{-1}\ Mpc^{-1}$ and the density parameters $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. Luminosity distances for each burst are calculated using the luminosity distance function provided by the 'astropy' Python package.

In order to get an approximate spectrum for the gamma ray background flux, we run a 2500 burst simulation over a detectable energy range of $100keV$ for a set of 5 different energy ranges: $100 - 200keV$, $150 - 250keV$, $200 - 300keV$, $300 - 400keV$, and $500 - 600keV$. Even though GRBs are diverse phenomenon, keeping the physical properties of each burst the same helps ensure that the properties of each energy range are relatively similar by reducing probability of error being introduced by a random number generator.

We assume approximately 2500 bursts take place over the course of a year. For every burst that is simulated, its intensity is averaged over one day and assigned a random day out of the year. Bursts that occur on the same day have their intensities summed together. After all unresolved bursts have been simulated, the average intensity for the whole year is taken which is value we compare to to observed DGRB.

In summary, we can break down the overall flow of the code into four basic steps.

1. **Initialize**: Define constants and functions then distribute blobs in a cone
2. **Distribute**: Generate a list of redshifts that match the proposed distribution.
3. **Calculate**: For each GRB, calculate the luminosity contribution from each blob over a narrow band using a randomized observation angle and a luminosity distance from our generated list.

4. **Average**: Find the average intensity from a single GRB over the course of 1 day. Sum together bursts that occur on the same day, then average then find the average daily intensity for the entire year.

2.5 Code testing

During the code development process, tests were performed to make sure the code worked as intended. Most of the tests we preformed were "sanity checks" such as the one reflected in Figure 1. We would mess with parameters in the code such as jet geometry, viewing angle, and GRB energy then look at the luminosity curves to make sure they changed in ways that would be expected. Additionally, units were throughly checked before and after every mathematical step to make sure the numbers coming out at the end were what we actually wanted.

3 Results

In table 2, we list the average observed gamma ray intensity generated using the methods described in the previous section.

Table 2: Data generated from the blob cone code using the parameters set in table 1

Energy Range $[keV]$	**Intensity** $[keV\ cm^{-2}\ s^{-1}\ sr^{-1}]$
100-200	1.33
150-250	0.61
200-300	0.42
300-400	0.29
500-600	0.027

The gamma ray background contribution from GRBs is highest at the $100-200keV$ photon energy range with an average observed intensity of $1.33kev\ cm^{-2}\ s^{-1}\ sr^{-1}$. After $400keV$, the observed intensity begins to drop off exponentially becoming nearly zero for any energy ranges after our $500-600keV$ simulation.

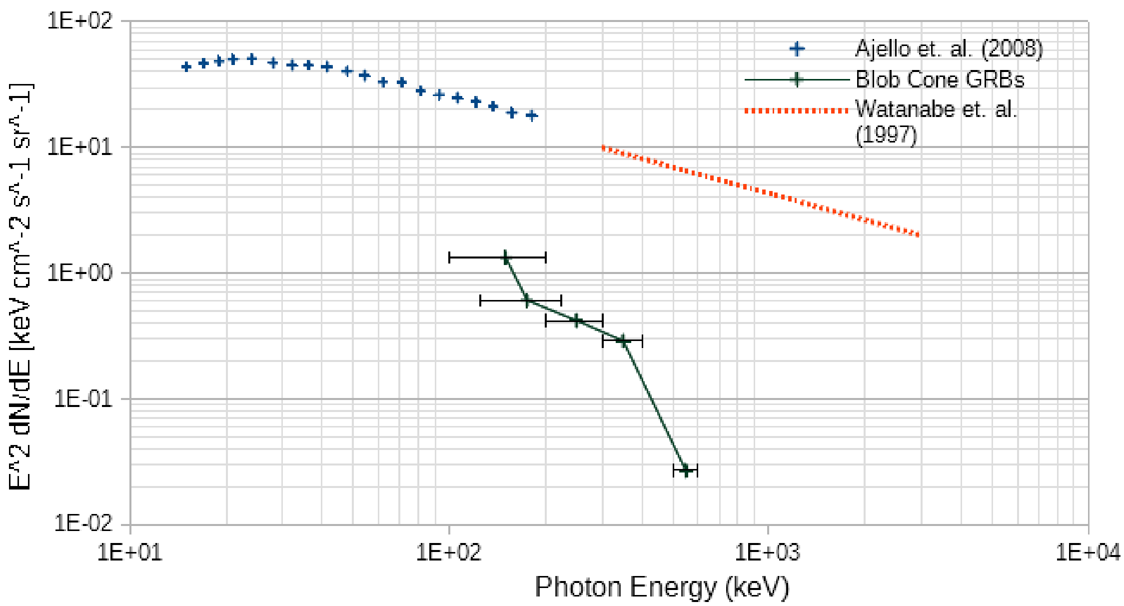

Figure 3: The diffuse gamma ray background over a range of $15-3000keV$. The blue crosses are the total observed DGRB compiled from the SWIFT and BATSE satellites as presented by Ajello *et al.* in [1]. The orange dashed lines are the approximate trend of data taken by the SMM satellite as is presented by Watanabe *et al.* in [12]. The connected green crosses represent the data generated by our code. Points are plotted at the midpoint of the range, the size of which is indicated by the error bars.

In Figure 3, we plot our simulated data against collected data in the energy range of interest. The highest contribution our GRB simulations happens over the $100-200keV$ range. The observed intensity as calculated by the blob cone simulator makes up about 7% of the observed gamma rays in that range. From $150keV$ to $400keV$, our simulated data follows approximately the same trend as seen in the observed data, but the GRB contribution to the total observed intensity drops to about 3%. After the $400keV$ range, the observed intensity from GRBs is less than 1% of what is actually observed.

4 Discussion

4.1 Discussion of results

The overall contribution of gamma rays from off-axis GRBs turns out to be quite low over the range tested ($< 10\%$). These low results, if they reflect reality, indicate that GRBs contribute very little to the observed DGRB. Type 1a Supernovae (SN1a) can account for some of observed gamma rays in our region tested, but recent simulations show SN1as to only account for about $20-50\%$ of the observed intensity [10] and then only in energy regions exceeding the regions tested by our blob cone model. In the SN1a models tested by RuizLapuente *et al.*, the gamma ray spectrum from supernovae does extend into the $100-600keV$ energy region, but cuts off sharply at energies less than $800keV$. In the lower energy regime, Seyfert galaxies and AGNs can account for nearly all of the observed gamma rays [6] [10] up to energies of about $150keV$ where the observed intensity from these sources begins to decrease cutting off exponentially at $300keV$ [10].

It should be said then, that the relativley low intensity contribution from GRBs may be the result of unphysical parameters set in the code. One such parameter is the choice we made for unresolved bursts. We assumed, somewhat arbitrarily, that if $\theta_{obs} < \theta_j + 2°$ then the GRB was resolved among the background. It may be the case that '$+2°$' to the jet opening angle is be too high of a guess for an off-axis burst causing us to throw out higher intensity bursts which would bring down our average observed intensity. Additionally, our assumed the rate at which GRBs occur may be off. We assumed that approximately 2500 bursts occur per year that might contribute to the DGRB, however the actual rate at which GRBS happen is still a subject that is not entirely established [8] [11].

4.2 Conclusions

While our code appears to work as intended, it is still not clear whether or not our results from the parameters set are physically reasonable. Other gamma ray sources studied, such as SN1as, AGNs, and Seyfert galaxies, don't appear to make up all the gamma ray intensity observed in the $200-500keV$ region. We found that in this region GRBs only make up about 3% of the observed intensity. It is possible however, that that parameters set for our simulations are not physical which calls for future simulations using a variety of different regimes. Until then, the observed gamma rays in the $200 - 500 keV$ region remain unexplained.

4.3 Future work

One improvement that can be made would be to run the simulations using more blobs per burst. While increasing the number of blobs would greatly increase computation time, it would reduce the overall luminosity contribution of each blob which would reduce non-physical errors introduced by the random number generators used to distribute the blobs in the burst. With fewer blobs per burst, there is a higher probability of the burst becoming "lopsided" that is, having more blobs distributed at an angle toward the observer and fewer blobs at an angle away from the observer or vice versa. The lopsidedness might make the burst appear more or less luminous than it should be depending on the distribution of blobs. Along the same line, running the code using more bursts would help smooth out any statistical outliers giving a better average intensity.

As discussed previously, only one set of physical parameters was used for our data, many of which are not well known. Future work would benefit from modifying the code to use a number of different parameter that more accurately fits a distribution of different GRBs. These parameters might include: fireball temperature, jet opening angle, blob activation/deactivation radii, GRB distribution, number of GRBs per year, and observation angle limit. All of these parameters play a crucial role in defining the observed intensity of a single GRB, by allowing them to change so that they better match a physical universe, their overall contribution to the DGRB will change.

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