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How Not to Miss the Supernova of the Century: Using Fermi GBM as an Alarm for a Future Galactic Type Ia Event

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A Galactic Type Ia Supernova (SNIa) could go entirely unnoticed to us due to the large optical and near-IR extinction in the Milky Way plane, low radio and X-ray luminosities, and a weak neutrino signal. But the recent SN2014J confirms that Type Ia supernovae emit nuclear gamma-ray lines, from the ^{56}Ni $\rightarrow^{56}$ Co $\rightarrow^{56}$ Fe radioactive decay. The lines last for weeks, and span from 158 keV to 2.6 MeV, squarely within the *Fermi* Gamma-ray Burst Monitor (GBM) energy range. The Milky Way is optically thin to gamma rays and GBM has continuous and nearly all-sky coverage, therefore the GBM is ideal to serve as a Galactic SNIa monitor and alarm. To illustrate the GBM capabilities, we use a simple model for SNIa gamma-ray emission and transfer to estimate MeV light curves and spectra. Our work is constrained and calibrated by SN2014J MeV data, which suggest $\sim$ 10% of the ^{56}Ni is in an optically thin belt surrounding the rest of the initially opaque ejecta. We estimate that the supernova signal emerges as distinct from the GBM background within the first days after the explosion in the SN2014J belt model. Therefore if a Galactic SNIa were to explode, GBM could confirm and sound the alarm possibly even on the first day of the explosion, and localize the SNIa to within $\sim$1 degree, using the Earth occultation technique.

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1. Introduction

Type Ia supernovae (SNIa) are cosmic-ray accelerators (e.g., [1, 2, 3]), nucleosynthesis sites of iron-group elements, and are used as standardizable candles. These events are thus important for cosmic-ray, particle and nuclear astrophysics, as well as cosmology. A Galactic SNIa, i.e., one exploding in the Milky Way, would of course provide unique insight into the SNIa phenomenon.

However, the Galactic SNIa rate is only about 1.4 events/century [4], meaning it's a "once in lifetime" event. Therefore if a SNIa were to explode in the Milky Way, it would be a great loss if it were missed. This unfortunately could be a real possibility. Although SNIa are enormously luminous at peak, a Galactic event should lie the plane of the Milky Way disk, and be highly obscured, e.g., $A_V \sim 30^{\rm mag}$ in the direction of the Galactic center. Adams et al. [4] construct a spatial model for the Milky Way spatial distributions of supernovae, and of Galactic extinction and reddening. They find that the expected optical extinction for Galactic SNIa is typically $> 10^{\rm mag}$, and can be much larger. Moreover, even if an event were quite bright, it may be confused with other transients like variable stars in the Galactic plane. The radio and soft X-ray emission from SNIa are also dim, confirmed by the non-detection of the nearest Type Ia event SN2014J [5, 6]. The SNIa neutrino emission has a much lower luminosity and a lower mean energy than for a core-collapse event, so that the neutrino signal from a SNIa explosion at $>$1 kpc will be too weak to be detected by current instruments on earth [7]. Moreover, a future Galactic SNIa could happen anywhere anytime in the Milky Way, most of which are not continually monitored at most wavelengths.

Fortunately, SNIa are confirmed gamma-ray emitters, through the radioactive decay series $^{56}{\rm Ni} \xrightarrow{8.8{\rm days}} {}^{56}{\rm Co} \xrightarrow{111.3{\rm days}} {}^{56}{\rm Fe}$. These thermonuclear explosions reach nuclear statistical equilibrium by burning such fuels as ^{12}C, ^{16}O, ^{20}Ne, and ^{24}Mg. These species have equal numbers of neutrons and protons, and thus the main nuclear statistical equilibrium product is the doubly-magic $^{56}_{28}{\rm Ni}^{28}$, which shares this same property [8]. In fact, SNIa light curves are powered by ^{56}Ni and ^{56}Co beta decays, which are accompanied by gamma-ray line emission spanning energies from 158keV to 2.6MeV. This line emission was confirmed by recent Type Ia supernova SN2014J in M82. Both radioactive nuclei ^{56}Ni and ^{56}Co lines were detected in gamma rays (^{56}Ni 158keV and 811keV lines; ^{56}Co 847keV and 1238keV lines). These lines were seen as early as about 20 days after the explosion [9, 10]. Core-collapse supernovae can also emit gamma-ray lines but with much lower luminosity, due to the lower ^{56}Ni yield, as observed in SN1987A (e.g., [11]). The Milky Way is optically thin to gamma rays, so the extinction of the SNIa line emissions is negligible.

The Gamma-ray Burst Monitor (GBM) on board *Fermi* consists of 12 NaI and 2 BGO scintillation detectors. The GBM is sensitive to the energy range between 8 keV and 40 MeV, and monitors ∼9.5 steradians of the (unocculted) sky at all times [1]. These properties make GBM an ideal Galactic SNIa monitor and alarm.

Our goal here is to show how to use the *Fermi*-GBM to monitor for a future Galactic SNIa, and to sound the alarm if we are so lucky that one occurs. The next section will briefly show our ejecta plus belt model to calculate the gamma-ray line emissions from a Galactic SNIa. Simulated light-curves and spectra in GBM and the comparisons with the typical background of the detector are presented in section 3. How we confirm the signal is from a Galactic SNIa and localize the

[1] http://fermi.gsfc.nasa.gov

SNIa with GBM is discussed in section 4.

2. Theoretical Model: Ejecta Plus Belt Model

To estimate a SNIa gamma-ray light curve and spectrum requires a model for the gamma-ray emission and transfer in the ejecta. Previous work made the assumption (plausible at the time) that SNIa are spherically symmetric and stratified (e.g., [12]). These calculations found that SNIa are opaque to gamma-rays for 100 days due largely to Compton scattering in the initially dense ejecta. If this were the case, then a Galactic SNIa would likely not be discovered by GBM until months after the explosion, delaying followup observations until well after the peak optical emission.

Fortunately, *INTEGRAL* observations of SN2014J detected ^{56}Ni lines within $\sim$20 days after the explosion, far earlier than expected. This initial line flux corresponds to about 10% of the total expected ^{56}Ni mass [9]. A possible explanation suggested by ref. [9] is the ^{56}Ni belt model, shown in Figure 1. In this model, there exists a belt of ^{56}Ni at the surface of the ejecta, with mass $M_{^{56}\mathrm{Ni,belt}}$, while the bulk of the ^{56}Ni (with mass $M_{^{56}\mathrm{Ni,int}}$) remains in the interior. At early times after the explosion, the ^{56}Ni decay photons in the belt are optically thin, while the interior decay photons remain optically thick.

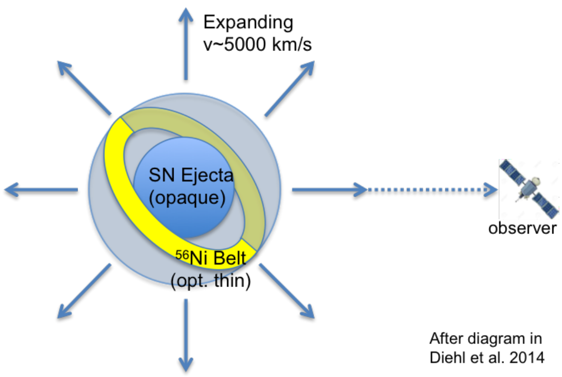

Figure 1: Sketch of the belt model, after diagram in ref. [9]. The ^{56}Ni belt at the surface of ejecta is optically thin to gamma rays while the ^{56}Ni inside the ejecta remains opaque during early days after the explosion.

We build a simple zeroth-order model to calculate the gamma-ray line emission flux from a Galactic SNIa. Ignoring the Compton continuum emission, the model combines [12]'s uniform ejecta model and [9]'s belt model to get the flux as:

$$\begin{aligned}\Phi_{^{56}\mathrm{Ni,total}}(E,t) &= \Phi_{^{56}\mathrm{Ni,ejecta}}(E,t) + \Phi_{^{56}\mathrm{Ni,belt}}(E,t) \\ &= \frac{M_{^{56}\mathrm{Ni,int}}}{M_{^{56}\mathrm{Ni,total}}}\phi(E,t)_{^{56}\mathrm{Ni,ejecta}} + \frac{M_{^{56}\mathrm{Ni,belt}}}{M_{^{56}\mathrm{Ni,total}}}\phi(E,t)_{^{56}\mathrm{Ni,belt}}\end{aligned} \tag{2.1}$$

where E is the gamma-ray photon energy, $M_{^{56}\mathrm{Ni,total}} = M_{^{56}\mathrm{Ni,int}} + M_{^{56}\mathrm{Ni,belt}}$ is the total ^{56}Ni mass produced in SNIa.

We adopt a uniform ejecta model, where the electron number density profile n_e is assumed to be flat in radius and drops to zero at the outer radius of ejecta $R = v_0 t$. Here v_0 is the velocity of the outer radius and is given by $v_0 = 1.295 \times 10^9 (M_{\rm ej}/M_\odot)^{-1/2} E_{51}^{1/2}$cm/s, $M_{\rm ej}$ is the total mass of the debris, E_{51} is the total kinetic energy in unit of 10^{51}ergs. For simplicity, ignoring Doppler shift, the optical depth to gamma rays is roughly $\tau = \int n_{\rm e} \sigma dl$ [12], where σ is the Thompson cross section. l is the pathlength of photons before escape. The volume of the ejecta is $V = 4\pi(v_0 t)^3/3$, $n_{\rm e} = n_{\rm p}/\mu_{\rm e} = M_{\rm ej}/(m_{\rm p}V)/\mu_{\rm e}$, $n_{\rm p}$ is the proton density, $\mu_{\rm e}$ is the mean baryon number per electron, $m_{\rm p}$ is the proton mass, $l \sim v_0 t$, so we can have $\tau \sim 3M_{\rm ej}\sigma/4\pi\mu_{\rm e} m_{\rm p} v_0^2 t^2$. For a Galactic SNIa, $M_{\rm ej} \sim M_{\rm Chandrasehkhar} = 1.4 M_\odot$, $\mu_{\rm e} = 2$, $\sigma \sim \sigma_{\rm Thompson} = 6.65 \times 10^{-25}{\rm cm}^2$, the optical depth is $\tau \sim (121.09{\rm day}/t)^2$, showing that after ~100 days, the ejecta is starting to be optically thin to gamma-ray photons.

Following ref. [12], and neglecting Doppler effects, we find the ^{56}Ni flux for line E_i to be:

$$\begin{aligned}\phi(E_i,t)_{^{56}{\rm Ni}} &= \frac{dN_\gamma}{dtdA} = \frac{b_{\rm E_i}}{4\pi D^2}\frac{M_{^{56}{\rm Ni,total}}}{56 m_{\rm p}}\frac{e^{-t/\tau_{^{56}{\rm Ni}}}}{\tau_{^{56}{\rm Ni}}} \cdot e^{-\tau} \\ &= 1.16 \times 10^3 {\rm cm}^{-2}{\rm s}^{-1}\frac{b_{\rm E_i}}{[D/10{\rm kpc}]^2} \cdot e^{-t/\tau_{^{56}{\rm Ni}}} \cdot e^{-\tau} \end{aligned} \tag{2.2}$$

where $b_{\rm E_i}$ is the branching ratio for the gamma-ray line at photon energy E_i, $\tau_{^{56}{\rm Ni}} = 8.8$days is the mean lifetime of the radioactive nickel ^{56}Ni, D is the distance of the SNIa. As shown in ref. [12], Doppler effects will broaden the decay lines.

Motivated by SN2014J, we assume a ^{56}Ni belt which is optically thin ($\tau = 0$) with $M_{^{56}{\rm Ni,belt}} = 0.05 M_\odot$ and $M_{^{56}{\rm Ni,total}} = 0.5 M_\odot$ [9]. In this model, the total ^{56}Ni gamma-ray line flux from both ejecta and belt is:

$$\Phi_{\rm Ni,total}(E_i,t) = 1.16 \times 10^3 {\rm cm}^{-2}{\rm s}^{-1}\frac{b_{\rm E_i}}{[D/10{\rm kpc}]^2} \cdot [0.9 e^{-(121.09{\rm day}/t)^2} + 0.1] \cdot e^{-t/\tau_{^{56}{\rm Ni}}} \tag{2.3}$$

Similarly, the total ^{56}Co gamma-ray line flux from both ejecta and belt is:

$$\Phi_{\rm Co,total}(E_i,t) = 99.5 {\rm cm}^{-2}{\rm s}^{-1}\frac{b_{\rm E_i}}{[D/10{\rm kpc}]^2} \cdot [0.9 e^{-(121.09{\rm day}/t)^2} + 0.1] \cdot [e^{-t/\tau_{^{56}{\rm Co}}} - e^{-t/\tau_{^{56}{\rm Ni}}}] \tag{2.4}$$

where $\tau_{^{56}{\rm Co}} = 111.3$days is the mean lifetime of ^{56}Co.

3. Simulated Results

Any supernova signal in the GBM must compete with the (time varying) background of gamma-rays always present. Above ~150 keV, the background sources are dominantly secondary gamma rays created by cosmic-ray interactions in the Earth's atmosphere, and in the spacecraft itself [13]. For a single BGO detector aboard GBM, with effective area $\sim 150{\rm cm}^2$ [14], the average background count rate is ~ 1700ph/s.[2]

The goal of GBM is to identify transients like the gamma-ray bursts that exceed the background emission. A typical gamma-ray burst rise timescale is a few seconds, for which GBM triggering is optimized. But the signal from a Galactic SNIa rise and decay lasts weeks ($\tau_{^{56}{\rm Ni}} =$

[2] http://fermi.gsfc.nasa.gov/science/mtgs/workshops/da2010_india/vc_gbm_science.pdf

8.8days, $\tau_{^{56}\mathrm{Co}} = 111.3$days), meaning the Galactic SNIa signal will appear as a long-duration increase in the detector's background, instead of triggering GBM detector. So we need to compare our simulation of light curves and spectra of a Galactic SNIa with a typical background of GBM detectors to check whether the signal is large enough to be noticed and how soon we can confirm a Galactic SNIa after its explosion and sound the alarm.

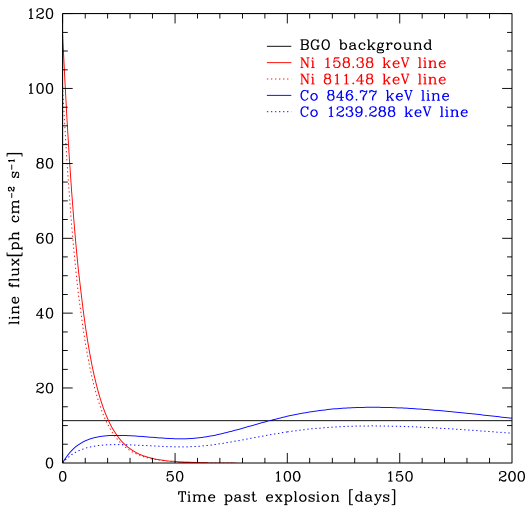

Figure 2: Preliminary simulation of light curves from a 10 kpc Galactic SNIa. Black solid line is the average background flux in the BGO detector. Blue lines are ^{56}Ni gamma-ray signal intensity variation for the 158 keV line (solid line) and the 811 keV line emissions (dashed line). Green lines are ^{56}Co gamma-ray signal intensity variation for the 847 keV line (solid line) and the 1238 keV line emissions (dashed line).

Our results depend on the supernova emission properties discussed above, but also on the distance D to the explosion. We adopt D = 10 kpc as a fiducial distance: this is comparable to the distance to the Galactic Center, and close to the most probable distance to a Galactic SNIa as found in ref. [4]. For other choices of distance, the flux and count rates will scale as $(10\mathrm{kpc}/\mathrm{D})^2$.

From equation 2.3 and equation 2.4, we can get the light curves of both ^{56}Ni and ^{56}Co decay gamma rays, shown in Figure 2. We can see that the line fluxes from ^{56}Ni decay are large compared to the BGO background, about 10 times higher than the background at the beginning. If the belt model is true, the ^{56}Ni decay signal from a Galactic SNIa will be noticed as early as first day after the explosion. ^{56}Co decay line fluxes are much smaller compared to ^{56}Ni, and exceed the BGO background flux after 100 days. But even for the line flux of ^{56}Co at $\sim$ 10 days, the signal of a single line emission is actually strong enough for GBM to detect ($\sim$ 50% of the BGO background).

With the same assumptions, we also compute simulated spectra of ^{56}Ni and ^{56}Co decay lines from a Galactic SNIa in a single BGO detector, for times 1 day and 20 days after the explosion. We assume the lines have a Gaussian profile, with Doppler broadening corresponding to a line-of-sight velocity of $\sim$ 5000km/s. The Compton scattering continuum is neglected here. The background spectra and response files of corresponding detectors are from HEASARC site.[3] The simulation is processed with Xspec.[4] The preliminary spectra seen in BGO detector are shown in Figure 3.

[3] http://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/

[4] http://heasarc.gsfc.nasa.gov/xanadu/xspec/

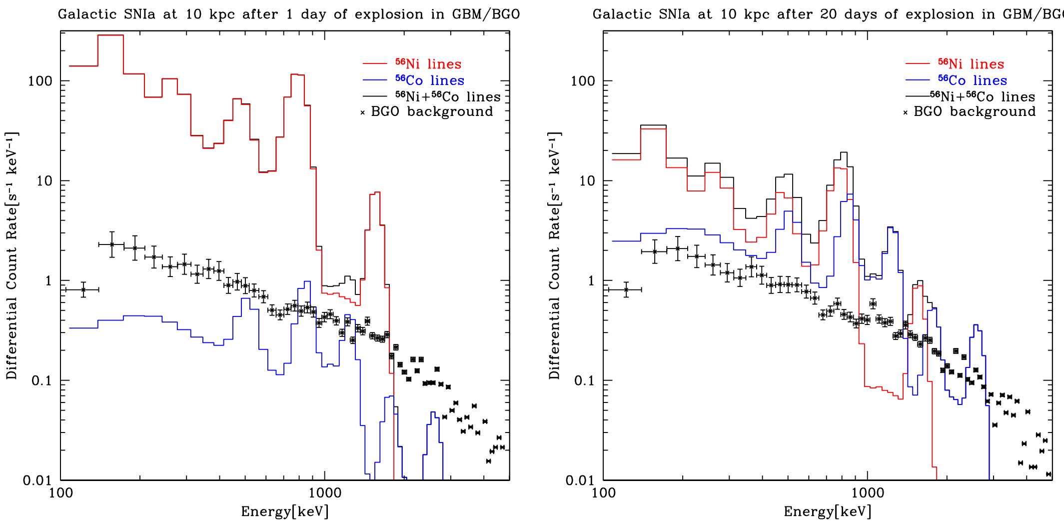

Figure 3: Preliminary simulation of ^{56}Ni and ^{56}Co gamma-ray lines signal seen in GBM BGO detector, from a 10 kpc Galactic SNIa after 1 day (above) and 20 days (below) of its explosion. The black data points represent a typical background spectrum from GBM BGO detector. Red solid line is the simulated ^{56}Ni decay lines signal, blue is ^{56}Co, and black is total signal of ^{56}Ni and ^{56}Co decay.

We can see that all of the ^{56}Ni lines are strong and distinct for a Galactic SNIa in both 1-day and 20-days simulation; the line fluxes vastly exceed the typical background. ^{56}Co lines signal is large enough to be seen after 20 days of the explosion, but even for first day, the two dominant ^{56}Co decay lines (847keV and 1238keV) are strong enough to be distinguished from the background signal. Thus, in the belt model we expect GBM could detect a Galactic supernova as soon as 1 day, with spectral line features from both ^{56}Ni and ^{56}Co serving to confirm the Type Ia origin of the explosion.

4. Discussion

We have seen that GBM can detect a Galactic SNIa within the first days of the explosion, if the SN2014J belt model is correct. In this scenario, both ^{56}Ni and ^{56}Co features should be present in the early spectra and confirm the supernova origin of the signal. Also, the gamma-ray lines' rise and decay with time should at least roughly follow the light curves we have presented.

After confirming the gamma-ray signal observed by GBM is from a future Galactic SNIa, we will use the Earth occultation technique to localize the SN on the sky. Because *Fermi* orbits the Earth with altitude 555 km $\sim 10\% R_{\oplus}$, about 30% of *Fermi*'s field of view is always blocked by the Earth. About 85% of the sky is occulted in one orbit, so that point sources will typically be eclipsed once per 90 min orbit, as seen in Figure 4. From the eclipse flux decrement and timing, sources can be identified and located. This technique has been successfully used to find known point sources in the GBM [15].

By associating the occulted time and the spacecraft's position, we can trace back the direction of the gamma-ray signal source. The occultation duration will depend on the elevation angle β between the source and the orbital plane. The angular resolution ranges from $\sim 0.5^\circ$ for $\beta = 0$

to $\sim 1.25^\circ$ for $\beta = 66^\circ$, and the timescale of localization is $\sim$P, where $P = 96$ minutes is *Fermi*'s orbital period. For $\beta > 66^\circ$, occultation does not occur, GBM need to wait to precess to another orbit to have signal blocked. The timescale of localization for this case will be much longer, ~ 26 days.

Once GMB has confirmed a Galactic SNIa and localized it to ~ 1 degree, followup observations at all other wavelengths should commence immediately. Particularly promising are optical/IR telescopes with large fields of view, such as DECam on the *Dark Energy Survey*, and later *LSST*. Moreover, followup from *Swift* could get better localization and complementary X-ray observation of the SN.

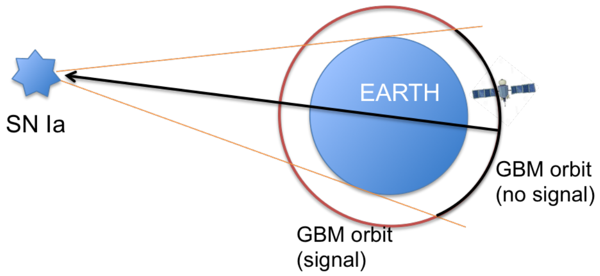

Figure 4: Sketch of how the Earth occultation technique localizes a Galactic SNIa.

In summary, a future Galactic SNIa may go unnoticed in virtually all electromagnetic wavelengths as well as in neutrinos, but will have a large gamma-ray signal observable in *Fermi*-GBM. The GBM is thus an ideal alarm for a future Galactic SNIa.

With the ^{56}Ni belt model, we can estimate that the alert timescale of a Galactic SNIa can be as short as first days after its explosion. Although the ^{56}Ni belt model seems required to understand SN2014J, it is not guaranteed that this model is correct, or applicable to all SNIa. When a SNIa signal will emerge above the GBM background depends upon the mass and distribution of ^{56}Ni in the ejecta. Therefore, future work will explore models with a range of ejecta structures (like mixed structure and "onion skin"), following ref. [16, 17]'s work and constrained by the SN2014J's gamma-ray data. We will then explore how the time for SNIa confirmation depends on the nature of the ejecta, thus linking the SNIa alarm to the nucleosynthesis and explosion physics.

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