A Comptonized Fireball Bubble Fits

the Second Extragalactic Magnetar Giant Flare GRB 231115A

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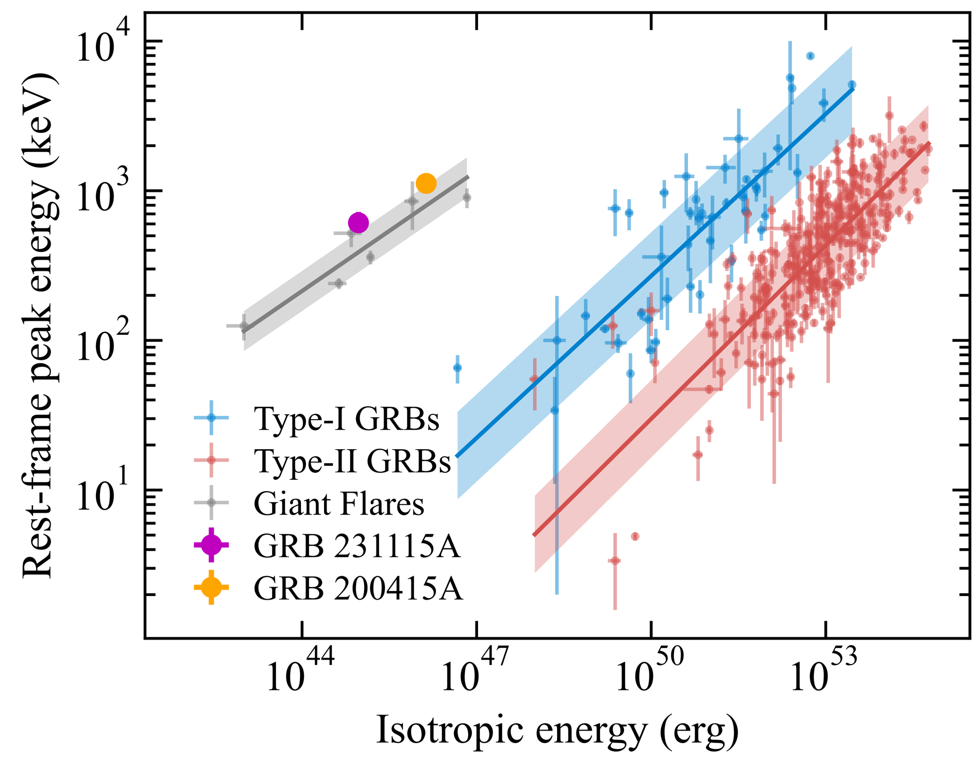
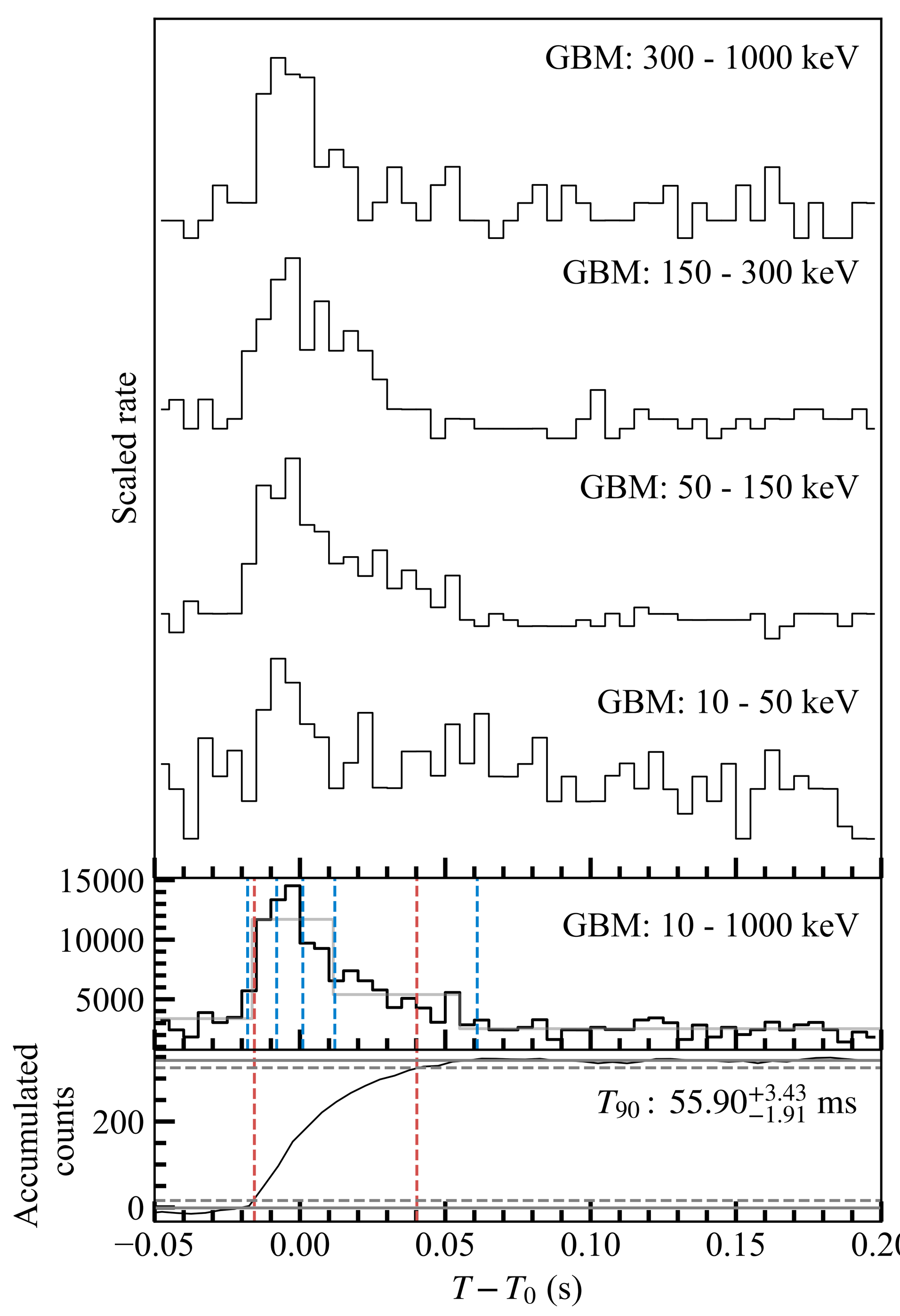
At 15:36:21.201 UT on 15 Nov 2023 (denoted as T_0), the Fermi Gamma-ray Burst Monitor (GBM) detected the MGF GRB 231115A [2, 4]. Almost immediately, INTEGRAL was also triggered by the event [3]. Subsequently, the positional data indicated alignment with the nearby galaxy M82, situated at luminosity distance of ~ 3.5 Mpc [1, 6]. Our derived peak energy and isotropic energy of the event from a Comptonized fireball bubble model further confirm the burst's MGF origin and its contribution to the MGF-GRB sample.



The $E_{pz} - E_{iso}$ correlation diagram. The red, blue, and gray solid lines represent the best-fit correlations for Type-I, Type-II, and MGF populations, respectively. The yellow dot marks the position of GRB 200415A from Yang et al. (2020) [8]. The purple dot marks the position of MGF GRB 231115A. All error bars on data points represent their 1-σ confidence level.

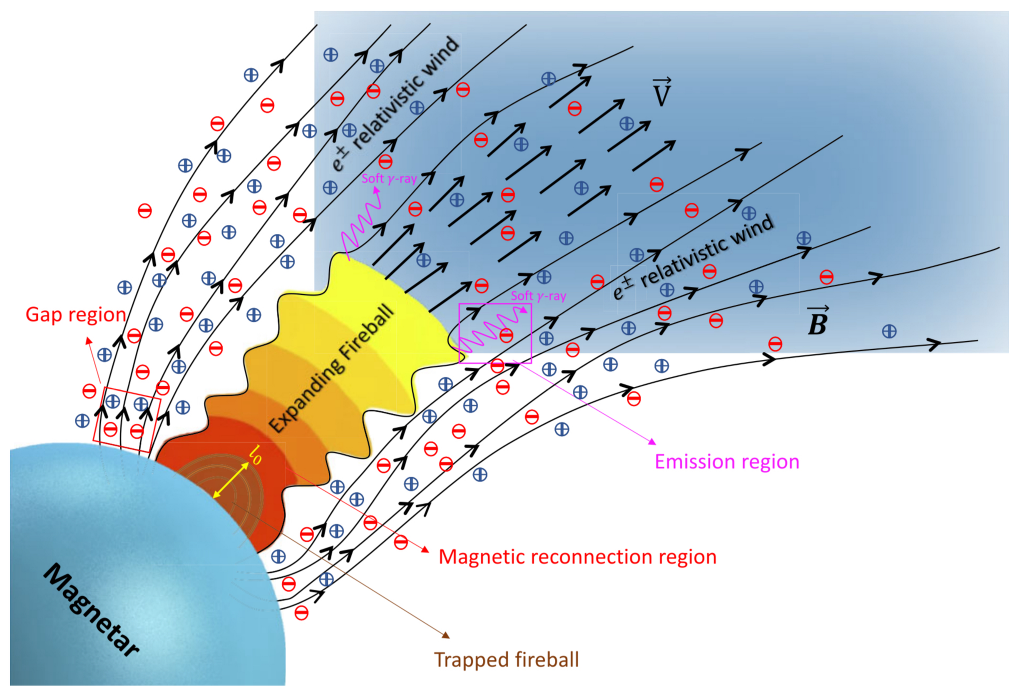
Temporal Properties

The event lasts for ~ 79 ms after T_0, exhibiting consistent pulse profiles in different energy ranges. We derived spectral lags between the lowest energy band (10-50 keV) and higher energy bands (50-150 keV, 150-300 keV, 300-1000 keV), revealing tiny values of $0.60^{+4.10}_{-4.30}$ ms, $2.20^{+4.90}_{-7.30}$ ms and $0.50^{+3.30}_{-2.70}$ ms, respectively. Half of the minimum bin size of the Bayesian blocks, 13.95 ms, is regarded as the minimum variability timescale of this event. Those temporal properties fall within the expected range for a short GRB, similar to GRB 200415A [8].



Multi-wavelength light curves of MGF GRB 231115A and T_{90} interval. The bin size is set to 5 ms for all light curves. The bottom two panels show the light curve of Fermi/GBM in the energy range of 10-1000 keV and the accumulated counts. The red dashed vertical lines represent the T_{90} interval. The gray curve corresponds to the derived Bayesian blocks from time-tagged event data. The blue dashed vertical lines mark four time slices for spectral analysis.

A Comptonized Fireball Model and Fit

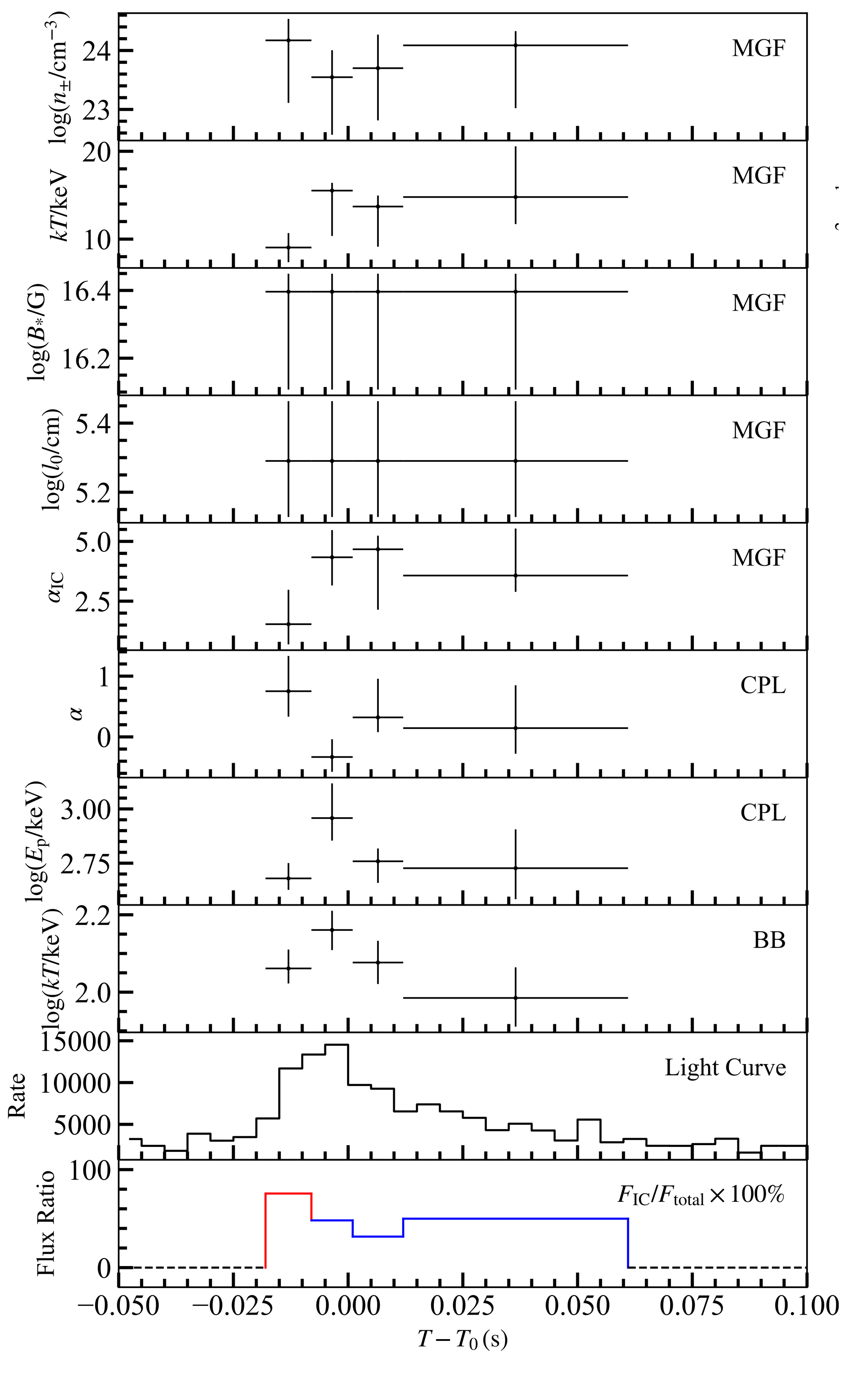


A schematic diagram of the Comptonized fireball model.

Consider a trapped fireball bubble, formed by photon-rich pair plasma captured by closed magnetic field lines, breaking free from its magnetic constraints and undergoing expansion toward the photosphere radius. Concurrently, due to the pressure from photon-pair plasma and the acceleration caused by the gap potential difference, a substantial number of $e^{\pm}$ pairs—characterized by high density and a thermal distribution—propagate along the magnetic field lines, forming a relativistic wind. Consequently, within the magnetar wind region, these relativistic $e^{\pm}$ pairs Comptonize the photons of the fireball, resulting in the production of high-energy gamma-ray emissions with a thermal-like distribution. Based on Zhang et al. (2023) [9], we modified the model and write the observed flux in the form of

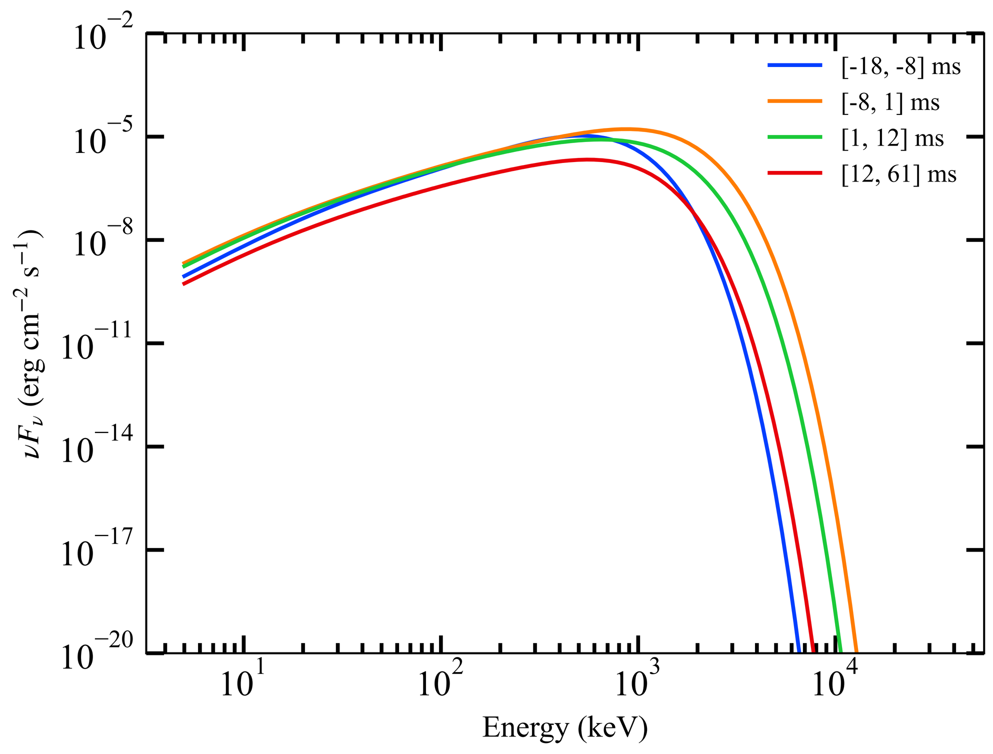
$$F_{\nu_{\rm obs}} = F^{\rm CC}_{\nu_{\rm obs}}(n_{\pm}, kT', B_*, l_0) + F^{\rm IC}_{\nu_{\rm obs}}(kT', \alpha_{\rm IC}, l_0), \qquad (1)$$

where $n_{\pm}$, T' and $\alpha_{\rm IC}$ are the number density of the $e^{\pm}$ in the emission region, the thermodynamic equilibrium temperature in the co-moving reference frame, and the index related to the IC intensity, respectively. l_0 denotes the initial radius of the expanding fireball. B_* stands for the local surface magnetic field of the magnetar, which is assumed to be constant across different time intervals.



The observed light curve of MGF GRB 231115A and its spectral evolution based on the best-fit parameters of the Comptonized fireball model, CPL, and BB models, along with the derived flux ratio between the IC process-dominated Wien spectrum and the entire spectrum in the energy range of 1-10000 keV. The red curve represents IC domination with an IC flux ratio surpassing 50%, while the blue curve represents CC domination with an IC flux ratio below 50%.

Under a strong magnetic field condition, the thermal photons of expanding fireball undergo two fundamental scattering processes: coherent Compton (CC) and incoherent inverse Compton (IC) scattering. Hence, the Comptonized fireball model anticipates a modified thermal-like spectrum characterized by three components, each predominantly influenced by the Rayleigh-Jeans regime, coherent Compton scattering and inverse Compton process, from the low-energy end to the high-energy tail.



The evolution of the νF_ν spectra as a function of the observed times.

Radiation Properties and Indications

1. l_0, well-constrained at 1.95×10^5 cm as a linked parameter in all time slices, provides us the radius of the trapped fireball.
2. Using the time-integrated spectra, we constrained the thermal energy of the expanding fireball in the co-moving frame $kT' \sim 12.73$ keV. The minimal radiation radius, l_x, of the expanding fireball is $\sim 1.09 \times 10^6$ cm. Then the value of the bulk Lorentz factor for the expanding fireball Γ is $\sim (l_x/l_0)^{3/2} \sim 13.30$. Utilizing Γ and kT', we can estimate the observed $kT_{\rm obs} = \Gamma kT' \sim 169.31$ keV. This estimation aligns with the temperature derived from the averaged BB spectrum, which stands at ~ 119.66 keV.
3. Initially, the IC process gives rise to a dominant Wien spectrum component, accounting for 75.59% of the entire flux. Subsequently, both CC and IC processes exert significant influence on the spectrum, with CC dominating the intermediate-energy region and IC prevailing in the high-energy region.
4. As the model requires small-scale magnetic field lines intertwining, the increase of line density could result in the local magnetic field surpassing 10^{16} G. The best-fit local surface magnetic field of the neutron star, B_*, yields a value of 2.51×10^{16} G, increasing the likelihood of detecting gravitational waves generated by magnetar oscillations [5]. This makes MGF GRBs promising candidates for kilohertz gravitational wave sources [7], especially if they can occur within our Galaxy.

References

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