PROCEEDINGS OF SCIENCE

Photospheric emission from long duration gamma-ray bursts powered by variable engines

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We present the results of a set of numerical simulations of long-duration gamma-ray burst jets aimed at studying the effect of a variable engine on the peak frequency of the photospheric emission. Our simulations follow the propagation of the jet inside the progenitor star, its break-out, and the subsequent expansion in the environment out to the photospheric radius. A constant and two step-function models are considered for the engine luminosity. We show that our synthetic light-curves follow a luminosity-peak frequency correlation analogous to the Golenetskii correlation found in long-duration gamma-ray burst observations. Within the parameter space explored, it appears that the central engine luminosity profile does not have a significant effect on the location of a gamma-ray burst in the Luminosity-peak frequency plane, bursts from different central engines being indistinguishable from each other.

Swift: 10 Years of Discovery
2-5 December 2014
La Sapienza University, Rome, Italy

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PoS(SWIFT 10)084

1. Introduction

Variability is commonly observed in GRBs [1], and a significant fraction of the long GRBs (∼85%) appear to be the result of several pulses [2]. The pre- and post-bursting activity, as well as dormant periods, still remain to be fully understood [3]. Fenimore & Ramirez-Ruiz [4] discovered a correlation between the variability and the observed peak isotropic luminosity. Thus, it is noteworthy to study the effects that a pulsed central engine has on the prompt GRB emission.

An important tool in the effort of finding common properties among the diversity of burst observations is the sample of correlations among different bursts or within bursts themselves. When having a GRB with variable behavior for example, each active pulse presents an intrinsic relationship between its peak frequency ($h\nu_{pk}$) and the correspondent isotropic luminosity (L_{iso}) [5, 6, 7]. The Golenetskii relationship shows that pulses with low L_{iso} peak at low frequencies, on the other hand when the burst is bright the peak frequency moves to higher frequencies. Thus, in order to check whether the photosphere-dominated from variable bursts obey this correlation, we carried out hydrodynamic numerical simulations of variable relativistic jets emerging from the interior of its correspondent progenitor star (within the collapsar scenario), and evolving through the interstellar medium (ISM).

2. Initial setup and numerical models

Three models of a variable relativistic two-dimensional (2D) jet were followed as they drilled through the stellar progenitor, and then as they evolved through an extremely large ISM domain. The progenitor, model 16TI from Woosley & Heger [8], was placed in a constant density interstellar medium ($\rho_{\rm ism}$=10^{-13} g cm^{-3}). Each of the variable jets were launched from the core of the progenitor and depending followed for over 100 s. The jet had at all times a half-opening angle θ_0=10^o at injection, an initial Lorentz Factor Γ_0=5, and a ratio of internal over rest-mass energy η_0=80. The jet models were (as shown in Figure 1):
a) A jet with forty 0.5 s with equal luminosity pulses (model m1)
b) A jet with forty 0.5 s with linearly decreasing luminosity pulses (model m2)
c) A single 20 s pulsed jet (model m3)

3. Results

The single pulsed model drills through the stellar envelope and breaks out of the progenitor (see the right panes in Figure 2). The jet is at all times low-density (ρ ∼10^{-3} g cm^{-3}), and before the jet breaks out of the star it is mildly relativistic. Once the jet breaks out of the star it reaches Γ ∼130 (at the photospheric radius ∼2×10^{12} cm). Meanwhile, the active phases of the variable models were low-density (ρ ∼10^{-3} g cm^{-3}) and mildly relativistic before the break out (Γ ∼10). The first nine pulses of model m1 (or seven for model m2) were destroyed as they created a funnel through the progenitor (as shown in the left panes of Figure 2). Each time a pulse was engulfed by the stellar envelope, the subsequent pulse managed to drill further out of the star. Once the variable jet broke out of the star, the pulse destruction ceased to occur and the subsequent pulses reached the photospheric radius.

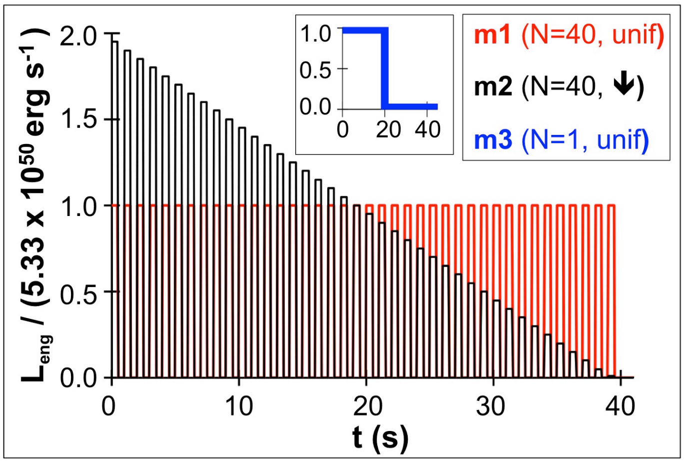

Figure 1: Engine luminosity for models m1 (red line), m2 (black line), and m3 (blue line).

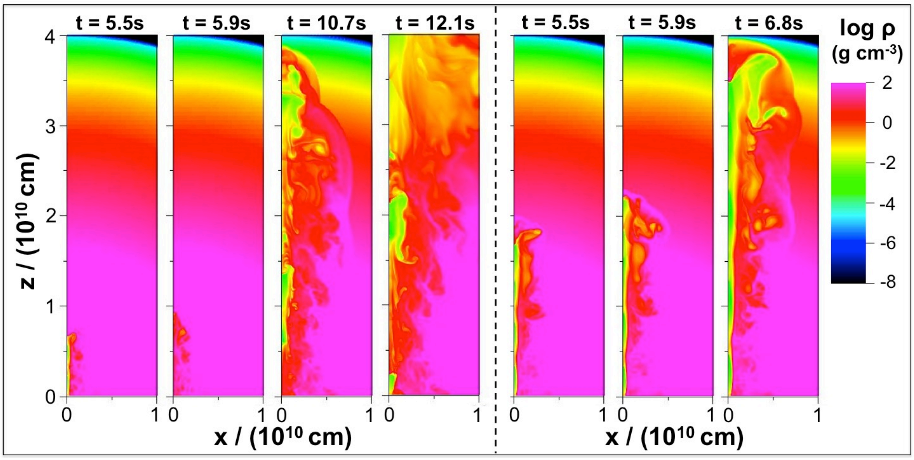

Figure 2: Density (g cm^{-3}) stratification maps for the variable jet (m1, 4 left panels), and for the single peak jet model (m3, 3 right panels) at different times.

Independently of the model, once the jet has broken out of the progenitor it evolves through the ISM and reaches the photospheric radius. The density and Γ stratification maps at different times for model m1 are illustrated in Figure 3. The pulses reach values close to $\rho \sim 10^{-6}$ g cm^{-3}, and Lorentz factors of $\Gamma \sim 80$.

In order to illustrate the relativistic motion of the pulses, Figure 4 shows the temporal evolution of the correspondent Γ for all three models (for an observer set at the photosphere radius with a $\theta = 1^o$ viewing angle). It is clear that the episodic jet models behavior is present at the photospheric radius and oscillates between $\Gamma = 10 - 80$.

The bolometric luminosity and the peak frequency emission were obtained following the same formalism as in [9]. The resulting light curves are shown in Figure 5. The photospheric light curve of the pulsed models also has an episodic behavior. Though there is not a clear one to one relationship between the launched pulses and the spikes in the light curve, the half a second pulses produce $\approx$1 s episodes, and with the luminosity ranging from 10^{52}erg s^{-1} to 4×10^{53}erg s^{-1}. This

PoS(SWIFT 10)084

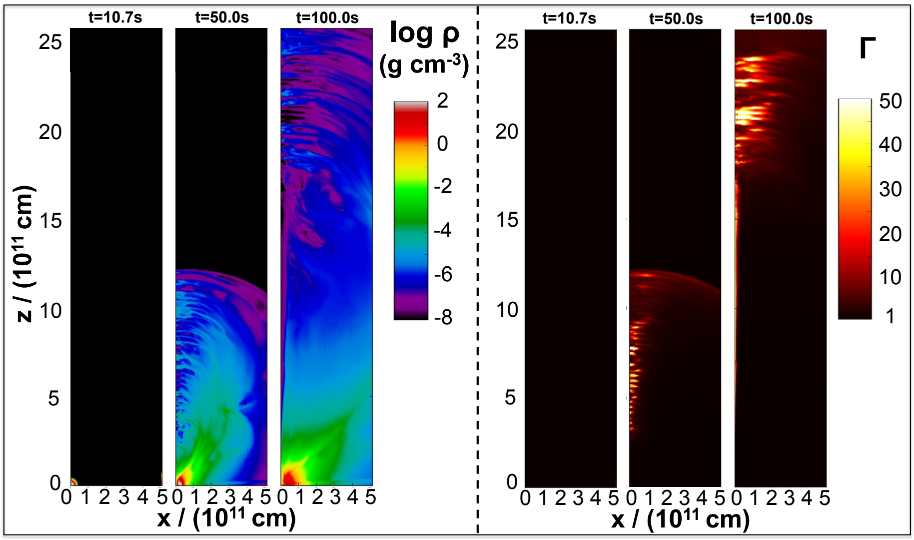

Figure 3: Density (g cm^{-3}) stratification maps (3 left panels), and Lorentz factor maps (3 right panels) for model m1.

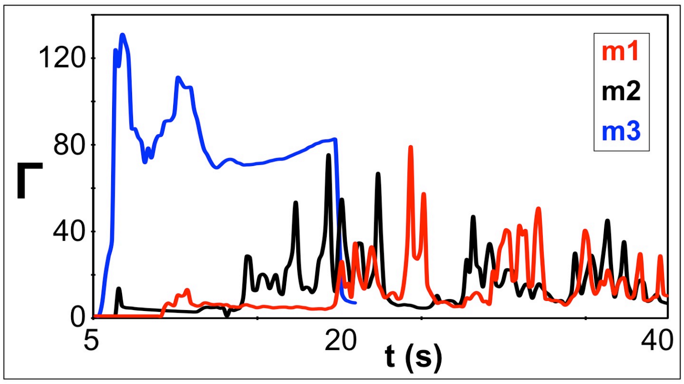

Figure 4: Temporal Lorentz factor evolution at $Z_{\rm obs}$ for models m1 (black), m2 (red), and m3 (blue).

behavior is not present in the single 20 s pulse model.

The peak frequency and corresponding isotropic luminosity were calculated for every pulse. The resulting relationship between the peak frequency and luminosity for each burst, as well as the Amati relationship are shown in Figure 6. The data from the synthetic light curves and spectra show agreement with the observations of Lu et al. [10].

4. Conclusions

The photospheric emission of jets from variable engines follows the Golenetskii correlation between the time-resolved luminosity and spectral peak. The synthetic light curves and spectra from our three models reproduce the Golenetskii and Amati correlations. Still, one must have in mind that while all GRBs from variable engines obey the correlation, outliers can be produced by engines of constant luminosity.

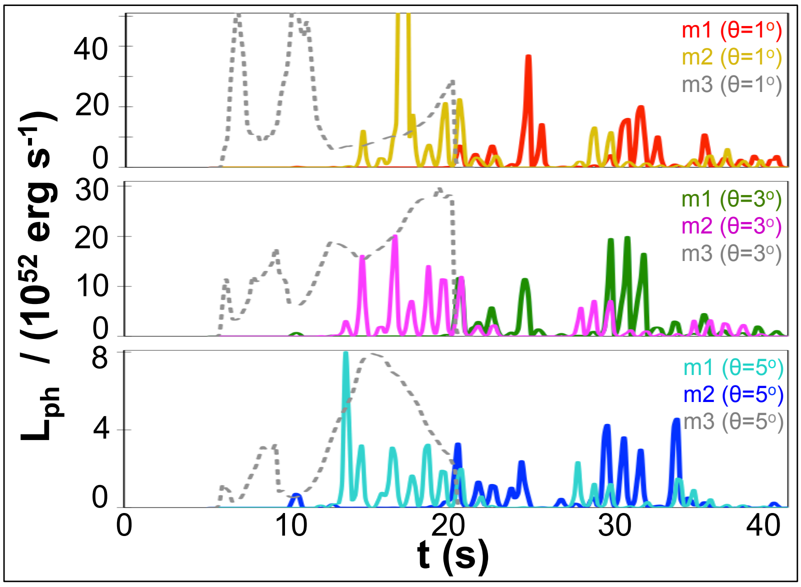

Figure 5: Photospheric light curves of the three models at different viewing angles (top panel is for θ=1^o, middle panel θ=3^o, and bottom panel θ=5^o).

5. Acknowledgements

We thank S.E. Woosley and A. Heger for making their pre-SN models available. The software used in this work was in part developed by the DOE-supported ASC/Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago. This work was supported in part by the Fermi GI program grant NNX12AO74G and Swift GI program grant NNX13A095G (DL and DLC). BJM is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-1102796.

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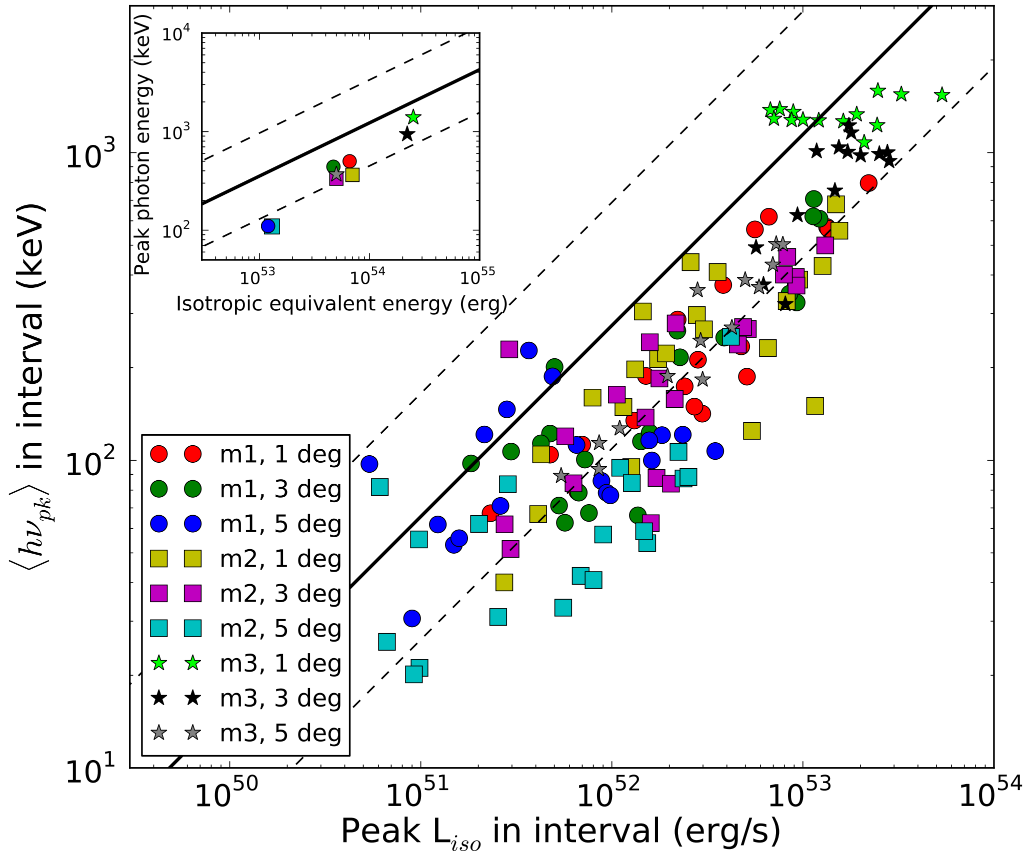

Figure 6: Synthetic Golenetskii correlation for models m1, m2 and m3 at various viewing angles, as indicated in the legend. The solid line represents the best fit of Fermi data of Lu et al. (2012) and their 2-sigma confidence (dashed lines). The inset shows the synthetic bursts on the Amati plane.

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