On the Nature of X-Ray Flashes

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Abstract. We have developed a toy model for internal shocks which has been used to generate a large number of synthetic GRBs in order to find in the parameter space the conditions which can lead to the formation of X-ray flashes. The key condition appears to be a small contrast of the Lorentz factor in the relativistic wind emitted by the central engine.

1. Introduction

The recently identified X-ray flashes (Kippen et al, 2002) have non thermal spectra with \(E_p < 50\) keV and weak gamma-ray fluxes (\(< 0.2\) ph.cm\(^{-2}\).s\(^{-1}\) in the 50 – 300 keV energy range). They were discovered by Beppo-SAX and are currently observed by HETE 2. They can be normal GRBs at very high redshifts (which however does not seem compatible with their duration distribution similar to that of long bursts) or viewed off-axis (Yamasaki et al, 2002) but their soft spectra can also have an intrinsic origin. We have tested this possibility in the context of the internal shock model where it is supposed that a central engine generates a relativistic wind with a non uniform distribution of the Lorentz factor.

2. A toy model for internal shocks

The evolution of this relativistic wind should be followed with a fully hydrodynamical calculation. This can be done (Daigne and Mochkovitch, 2000) but requires large amounts of computing time which prevents to consider a large number of cases and fully explore the parameter space. These detailed calculations have however shown that a simplified approach where the wind is represented by many shells which interact by direct collisions only (all pressure waves being neglected) can also produce satisfactory results (Kobayashi, Piran and Sari, 1997; Daigne and Mochkovitch, 1998). Going a step further we have developed for this study a toy model where internal shocks are limited to the collision of two shells of equal mass \(m\). Shell 2 (Lorentz factor \(\Gamma_2\)) is generated a time \(\tau\) after shell 1 (Lorentz factor \(\Gamma_1 < \Gamma_2\)). The average power injected into
the wind in this two shell approximation is given by

$$\dot{E} = \frac{mc^2}{\tau} (\Gamma_1 + \Gamma_2) = \dot{M} \bar{\Gamma} c^2$$ (1)

where $\dot{M} = 2m/\tau$ and $\bar{\Gamma} = \frac{1}{2} (\Gamma_1 + \Gamma_2)$ are the average mass loss rate and Lorentz factor. Shell 2 will catch up with shell 1 at the shock radius $r_s = 2c\tau \Gamma_2^{-1} \Gamma_2^{-2} - \Gamma_2^{-1} \Gamma_2^{-2}$.

The two shells merge and the energy dissipated in the collision $E_{\text{diss}}$ is radiated with a characteristic broken power law spectrum. If the synchrotron process is responsible for the emission, the peak energy (maximum of $\nu F_\nu$) is

$$E_p \simeq E_{\text{syn}} \propto \Gamma_s B \Gamma_2 \rho_s^x \epsilon_s^y$$ (2)

In the last term $\rho_s$ and $\epsilon_s$ are respectively the typical density and dissipated energy (per unit mass) in the comoving frame of the shocked material. The standard equipartition assumptions correspond to $x = 1/2$ and $y = 5/2$ but we consider below the possibility that $x$ and $y$ can have different values. This may be for example the case if the equipartition parameters $\alpha_B$ and $\alpha_e$ which fix the fraction of dissipated energy injected into the magnetic field and the relativistic electrons are not constant but depend on $\rho_s$ or/and $\epsilon_s$.

The physical properties of the shocked material $\Gamma_s$, $\rho_s$ and $\epsilon_s$ can be directly related to the wind parameters $\tau$, $\dot{E}$, $\bar{\Gamma}$ and $\kappa = \Gamma_2/\Gamma_1$ so that eq.(2) can be expressed as

$$E_p \propto \frac{\dot{E}^x \varphi_{xy}(\kappa)}{\tau^{2x} \Gamma^{6x-1}}$$ (3)

where $\varphi_{xy}(\kappa)$ is an increasing function of $\kappa$ for all reasonable values of $x$ and $y$. In spite of the simplicity of the two shell approximation eq.(3) predicts a duration-hardness relation and a hardness-intensity correlation (HIC) as observed in real bursts. Another interesting (and surprising) consequence of eq.(3) is that $E_p$ is a decreasing function of $\bar{\Gamma}$ as long as $x > 1/6$. Soft bursts are obtained with “clean fireballs” (large $\bar{\Gamma}$) while winds with larger baryon loads (“dirty fireballs”) lead to a harder spectrum because internal shocks occur closer to the source at a higher density.

From the values of $E_{\text{diss}}$, $\tau$, $E_{\text{break}}$ and assuming a Band spectrum with low and high energy indices $\alpha = -1$ and $\beta = -2.5$ it is possible to estimate (for a given redshift) the average flux or count rate in any spectral band. The simplicity of the two shell approximation then allows to construct a large number of synthetic bursts to check if XRFs can be formed for some specific choice of the wind parameters.

3. A statistical approach

The redshift $z$ and the four wind parameters $\tau$, $\dot{E}$, $\bar{\Gamma}$ and $\kappa$ have been obtained in a statistical way for each synthetic burst. If long GRBs (and XRFs) are related to the explosive death of some special class of massive stars their birth rate is directly proportional to the star formation rate $\psi$ and their distribution in redshift can be deduced from $\psi(z)$ (Porciani and Madau, 2001). The distribution
of the observed duration \( t_{90} \) for long bursts is log-normal with a maximum at \( t_{90} \sim 20 \) s. We therefore also take a log-normal distribution for \( \tau \) (with a maximum at \( \tau_{\text{max}} = 10 \) s) assuming an average burst redshift \( \langle z \rangle \sim 1 \). The last three wind parameters \( \dot{E}, \Gamma \) and \( \kappa \) are very poorly constrained and we adopt for them uniform distributions: between 50 and 53 for \( \log \dot{E} \), 100 and 500 for \( \Gamma \), 0 and 1 for \( \log \kappa \).

We performed a first numerical experiment with \( 10^6 \) synthetic bursts to obtain their \( E_p \) distribution. The results are shown in Fig.1 for two choices of \( x \) and \( y \): \( x = 1/2 \) and \( y = 5/2 \) i.e. synchrotron emission with standard equipartition assumptions and \( x = y = 1/4 \). This last case was already considered by Daigne and Mochkovitch (2003) who have shown that it leads to very good fits of the temporal and spectral properties of individual GRB pulses. The dashed line in Fig.1 represents the distribution of \( E_p \) for all \( 10^6 \) bursts while the full line corresponds to the sub-group of bursts which would have been detected by BATSE (a threshold of 0.2 ph.cm\(^{-2}\).s\(^{-1}\) in the 50 – 300 keV energy band was assumed). It can be seen that for \( x = 1/2 \) and \( y = 5/2 \) the distribution of \( E_p \) is much too wide while the agreement with the observations is excellent for \( x = y = 1/4 \). Figure 1 also shows that a large fraction of events with \( E_p < 100 \) keV is not detected by BATSE but may contribute to the population of XRFs seen by Beppo-SAX and HETE 2.

To test this possibility we have generated (assuming \( x = y = 1/4 \)) 1000 events for which we compute both \( E_p \) and the photon flux in the 50 – 300 keV band. The results are compared to the BATSE + Beppo-SAX data (Kippen et al, 2002) in Fig.2. Small dots represent BATSE bursts while large dots are events which are not detected by BATSE but have an X-ray flux (2 – 10 keV) larger than 1 ph.cm\(^{-2}\).s\(^{-1}\). The similarity between the two diagrams clearly shows that XRFs can be produced in the context of the internal shock model.
We then obtained the distributions of $z$, $\tau$, $\dot{E}$, $\bar{\Gamma}$ and $\kappa$ for synthetic XRFs. Their redshift distribution is nearly identical to that of GRBs and our simulation therefore confirms that XRFs are not GRBs at very high redshifts. The duration and injected power distributions are also not very different between XRFs and GRBs and it finally appears that a reduction of the contrast $\kappa = \Gamma_2/\Gamma_1$ and an increase of the average Lorentz factor $\bar{\Gamma}$ are the most efficient ways to produce XRFs. The distribution of $\kappa$ has a sharp maximum at about 1.5 in XRFs while it steadily increases (and is negligible for $\kappa < 2$) in GRBs. There are also five times more XRFs with $\bar{\Gamma} = 500$ than with $\bar{\Gamma} = 100$.

4. Conclusion

Our simulations have shown that XRFs can be produced by internal shocks if the Lorentz factor in the relativistic wind has variations of small amplitude only and a high average value. XRFs are not the result of a low injected power $\dot{E}$ but are weak and soft mainly due to a small contrast of the Lorentz factor which leads to a reduced efficiency of the dissipation in shocks.

References

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