X–ray spectroscopy of γ-ray bursts: the path to the progenitor

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Abstract. Despite great observational and theoretical effort, the burst progenitor is still a mysterious object. It is generally accepted that one of the best ways to unveil its nature is the study of the properties of the close environment in which the explosion takes place. We discuss the potentiality and feasibility of time resolved X–ray spectroscopy, focusing on the prompt γ-ray phase. We show that the study of absorption features (or continuum absorption) can reveal the radial structure of the close environment, unaccessible with different techniques. We discuss the detection of absorption in the prompt and afterglow spectra of several bursts, showing how these are consistent with gamma-ray bursts taking place in dense regions. In particular, we show that the radius and density of the surrounding cloud can be measured through the evolution of the column density in the prompt burst phase. The derived cloud properties are similar to those of the star forming cocoons and globules within molecular clouds. We conclude that the burst are likely associated with the final evolutionary stages of massive stars.

INTRODUCTION

It is widely believed that a good way to understand which is the progenitor of GRBs is by analyzing the properties of the interstellar medium that surrounds the explosion. This is because the fireball early self–similar evolution erases all the traces of its initial condition and hence any pre and during–explosion signature.

The three main classes of burst progenitor can be, in principle, easily distinguished by mean of the properties of their environment. If the burst are due to the merger event of binary coalescing systems of neutron stars [1] they are expected to take place in a uniform low density \((n \sim 0.1 – 10 \text{ cm}^{-3})\) intergalactic medium. This is due to the fact that the binary system has a long life \((\sim 10^9 \text{ y})\) and a high proper motion \((v \sim 100 – 1000 \text{ km/s})\) and can travel out of the original birth place before the merging event (but see Perna et al., this volume)

If the explosion of a GRB is coincident with the explosion of a massive rotating star (hypernova or collapsar, Woosley, this volume), it has to be surrounded primarily by the pre–explosion stellar wind. This wind will then impact on the molecular cloud in which the star was born, with a shock contact (terminal) discontinuity [2].

Finally, the bursts may be associated to supernova explosions but with some delay (see the supranova model [3]). In this case the burst should explode in an evacuated cavity, surrounded by a supernova shell and eventually by a molecular cloud medium.

These three radial profiles of the ambient media surrounding GRBs are sketched in the left panel of Fig. 1, where the solid line represents compact mergers and the dashed and dotted lines represent hypernovae and supranovae, respectively.

In principle the density profile can be traced by modelling the afterglow light curves and spectra. One must however be aware that most afterglow data are taken between half a day and several months after the burst explosion. As it is shown in the right panel of Fig. 1, in this period of time the fireball, no matter the progenitor model, runs through a uniform medium, the only difference being the normalization (probably the most uncertain of all the model parameters). The morphological difference of the left panel is then impossible to reconstruct with present day measurements.

There are several alternatives in order to measure the close environment density and structure. One is to be fast. In principle, if one can have (as we will have in the Swift era) detailed early time light curves, the whole radial density structure can be measured. However, it is likely that the emission mechanism of the afterglow gets more complicated as we approach the explosion site: reverse shock emission, late injection of energy from the inner engine and the superposition with the radiation from internal shocks will probably make the modeling of early time afterglows a delicate issue.
FIGURE 1. Radial density profiles for different GRB progenitors. The solid line represents compact mergers and the dashed and dotted lines represent hypernovae and supranovae, respectively. The left panel shows the pre-explosion setup, while in the right panel only the range of radii that the fireball travels between an observer time $t = 12$ hours and $t = 2$ months is highlighted.

FIGURE 2. Opacity in the range [2-10] keV for a cloud with solar metallicity, $R = 3 \times 10^{18}$ cm and initial column density $N_H(0) = 3 \times 10^{21}$ cm$^{-2}$. In the main panel, from top to bottom, we plot the absorption at times $t = 0, 10, 40, 80, 120$ and 160 seconds. In the inset, the column density is shown as a function of time. Filled dots mark the column densities corresponding to the spectra plotted in the main panel.

An alternative is to look for echoes, i.e. photons that, initially emitted at large angles with respect to the line of sight, are scattered in the direction of the observer. Dust [4], Compton [5] and iron line [6] echoes have been proposed. Only iron lines have been securely observed, to date [7]. The modelling of echoes presents two difficulties: first, if GRB fireballs are highly collimated, there is little room for echoes. Secondly, it is difficult to disentangle photons scattered by a large angle at small distance from the burst site from photons scattered at small angles at a larger distance from the progenitor.

We here propose and analyze a method, based on prompt time-resolved X-ray spectroscopy of the burst photons, which is unbiased and rely on very well known physics. The propagation of the photons in the ambient medium will in fact imprint absorption features on the soft X-ray spectra. These features will become less deep as the ionization front expands, allowing us to measure the density and the radial profile of the surrounding material.

**COLUMN DENSITY EVOLUTION**

There are in principle two ways of exploiting time-resolved X-ray spectroscopy. In case of very good quality data, one can follow the opacity vs. time of a single, well
FIGURE 3. Evolution of the column density with time for a uniform (solid line) and shell (dashed line) environments. In both cases the initial column density is $N_H(0) = 10^{23}$ cm$^{-2}$ and the outer radius is $R = 1$ pc.

isolated feature. An example is the iron $K_\alpha$ photoionization edge [8, 9] at 7.1 keV. This has the advantage of being completely model independent. On the other hand, the opacity of the iron edge for solar metallicity material is very small, and a Thomson thick cloud is necessary in order to observe a $\tau_{Fe} > 1$ feature.

At lower energies ([0.1-2] keV), the spectra are more crowded and it is very difficult to follow a single transition. However, the opacity is much larger, and even a $\tau_T < 0.01$ cloud can yield a very easily measurable signal. Usually the quantity of absorbing material is parametrized through the quantity $N_H$, i.e. the column of solar metallicity cold material that would absorb the same quantity of soft X–ray photons.

In the case of material surrounding GRBs, the assumption of solar metallicity can be reasonable, but the measured $N_H$ is much different from the real column density due to the progressive ionization the medium undergoes as the burst photons propagate through it. In order to estimate the amount of absorbing material as a function of time (which will show as $N_H$ in the spectra) we run many photoionization simulations (see [10] for more details). Fig. 2 shows the result of one of these simulations, in terms of the frequency–resolved time dependent opacity (main panel) and of the measured column density (inset). The advantage of the method is that different radial density profiles will give different time evolutions of the $N_H$ evaporation. For example, Fig. 3 shows the case of a uniform cloud and of a shell with the same initial column density. The shell material is more difficult to photoionize and the column density evolution is then slower.

Application to GRB data

Even though with limited spectral resolution and statistical quality, some time resolved column density measurement have been performed with real data. We show in Fig. 4 and Fig. 5 the cases of GRB 980329 [11], observed with BeppoSAX and GRB 780506 [12]. In both cases a fairly dense and compact region is derived as a best fit to the data. The radial profile could not be measured since in one case (GRB 980329) the error bars of the measurement were too large and in the other (GRB 780506) only one positive detection was made.

DISCUSSION

We have shown that time resolved X–ray spectroscopy of the early phases of GRB emission can give us informations on the density and radial structure of the surrounding material. Given the capabilities of present days instrumentations, this can be effectively done in case of fairly dense and compact regions. If we impose that the
column density must not be negligible after 1 second of observation and that it must decrease by a factor of two after 100 seconds of GRB emission, we find that, for a uniform absorbing cloud, positive detections of \( N_H \) variations should be performed if a GRB is surrounded by a cloud with size and column density marked with the gray shading in Fig. 6.

We compared these cloud properties with typical properties of molecular clouds and their overdense regions in our Galaxy. We find that if GRBs take place in random locations inside molecular clouds, their X-ray early spectra should show no sign of photoionization absorption, since all the material is ionized on a time scale of less than one second. On the other hand, massive stars are thought to be born inside overdense and compact regions within molecular clouds. If GRBs are associated with these regions, evolution of the X-ray absorbing column should be detectable. In particular, the variable absorption observed in the spectra of GRB 980329 and GRB 780506 can be explained if they were located in regions with properties close to those of Bok globules.

REFERENCES

1. Eichler, D., Livio, M., Piran, T., and Schramm, D. N., *Nature*, 340, 126–128 (1989).
2. Ramirez-Ruiz, E., Dray, L. M., Madau, P., and Tout, C. A., *MNRAS*, 327, 829–840 (2001).
3. Vietri, M., and Stella, L., *ApJ*, 507, L45–L48 (1998).
4. Esin, A. A., and Blandford, R., *ApJ*, 534, L151–L154 (2000).
5. Madau, P., Blandford, R. D., and Rees, M. J., *ApJ*, 541, 712–719 (2000).
6. Lazzati, D., Campana, S., and Ghisellini, G., *MNRAS*, 304, L31–L35 (1999).
7. Piro, L. e. a., *Science*, 290, 955–958 (2000).
8. Lazzati, D., Perna, R., and Ghisellini, G., *MNRAS*, 325, L19–L23 (2001).
9. Lazzati, D., Ghisellini, G., Amati, L., Frontera, F., Vietri, M., and Stella, L., *ApJ*, 556, 471–478 (2001).
10. Lazzati, D., and Perna, R., *MNRAS in press (astro-ph/0110486)* (2001).
11. Frontera, F. e. a., *ApJS*, 127, 59–78 (2000).
12. Connors, A., and Hueter, G. J., *ApJ*, 501, 307+ (1998).