Early afterglows as probes for the reionization epoch

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Abstract. The nature of Gamma–Ray Burst (GRB) progenitors is still a debated issue, but consensus is growing on the association of GRBs with massive stars. Furthermore, current models for the reionization of the universe consider massive Pop–III stars as the sources of the ionizing photons. There could then be a natural link between GRBs and reionization. The reionization epoch can be measured through prompt IR spectral observations of high redshift GRBs. For this, GRBs are better than quasars: they produce a smaller HII region even if they are much brighter than quasars (but for a much shorter time) and then, contrary to quasars, they do not modify the absorption properties of the surrounding IGM.

1 Introduction

The importance of Gamma–Ray bursts (GRB) for cosmological studies has been realized immediately after the measure of the first high–redshift bursts (GRB971214: Kulkarni et al., 1998 and GRB 000131: Andersen et al., 2000). Their importance for cosmological studies is based on observed properties and on the likely association with very massive stars:

- For a few hours, the early afterglow flux in the NIR, optical and X–ray bands is larger than the flux from any other cosmological object;
- The afterglow brightness depends very weakly on redshift, given its time evolution and spectral properties (Ciardi & Loeb, 2000);
- GRBs are probably connected with the death of massive stars and can hence be used to investigate the star formation rate at very high redshift, (see, e.g., Lamb & Reichart, 2000);
- GRBs are likely linked to the Pop–III objects and hence to the reionization of the universe (see, e.g. Rees 2000);

We here concentrate on the use of GRBs for the measurement of the redshift of the reionization of the intergalactic medium (IGM).

This measurement is made difficult by the fact that the opacity of the IGM is given by (see, e.g., Madau & Rees, 2000):

$$\tau(z) = 1.5 \times 10^5 h^{-1} \Omega_M^{-1/2} \frac{\Omega_b h^2}{0.019} \left(\frac{1 + z}{8}\right)^{3/2}$$  \hspace{1cm} (1)
implying that at high redshift \( z > 2 \), even if only a hydrogen atom over \( 10^4 \) is neutral, yet the universe has a huge \( (\tau \sim 10) \) opacity to UV photons.

Since all observed quasars have a strong Lyman–\( \alpha \) line in emission in their spectra, it has been speculated that the discovery of a quasar without an emission Lyman–\( \alpha \) line proves its location at a redshift larger than reionization. On the other hand, Madau & Rees (2000) have shown that a quasar is always surrounded by a large \( \text{HII} \) region. This implies that the Lyman–\( \alpha \) photons produced by the central source will be redshifted at a lower frequency before reaching the edge of the \( \text{HII} \) region, and will not be scattered by neutral hydrogen any more. The presence/absence of Lyman–\( \alpha \) emission line in QSO spectra is then not a probe of the reionization epoch.

We here show a possible solution: a GRB is more luminous than a quasar but, since its duty cycle is much shorter, the total number of ionizing photons is smaller and the size of the \( \text{HII} \) region smaller.

### 2 Strömgren spheres

An important advantage of GRBs with respect to QSOs for cosmological use is the dimension of the Strömgren sphere surrounding them.

Consider a source which radiates ultraviolet photons. The recombination time of the hydrogen with interstellar medium densities, even at redshift of order 10 and in presence of moderate clumping, is longer than 1 Gy (Madau & Rees, 2000). In these conditions, the radius of the \( \text{HII} \) region surrounding the photon source is obtained by equating the number of hydrogen atoms within a certain volume with the number of ionizing photons emitted during the life of the source itself. We obtain:

\[
R = \left( \frac{3 \dot{N}_{\text{ion}} t}{4\pi n_H} \right)^{1/3},
\]

where \( \dot{N}_{\text{ion}} \) is the ionizing photon rate, \( t \) is the lifetime of the photon source and \( n_H \) the hydrogen number density.

By adopting fiducial values for the luminosity and the duty cycle of a quasar and a GRB, we obtain:

\[
R_{\text{QSO}} = 1.5 \times 10^5 \, L_{46}^{1/3} \, t_{15}^{1/3} \, n_H^{-1/3} \, \text{pc}; \quad R_{\text{GRB}} = 70 \, L_{46}^{1/3} \, t_{15}^{1/3} \, n_H^{-1/3} \, \text{pc} \tag{3}
\]

There is then a factor greater than 1000 between the size of the \( \text{HII} \) region of a GRB, (which remains well within a galaxy), and the size of the \( \text{HII} \) region of a QSO. In particular, the size of the Strömgren sphere of the quasar is so large that a Lyman–\( \alpha \) line emitted by the central object can travel through an opaque universe and be observed at infinity. This happens because the line photons would be redshifted outside the Lyman–\( \alpha \) resonance before reaching the edge of the \( \text{HII} \) region (Madau & Rees, 2000; Cen & Haiman, 2000).

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1 Here and in the following we parameterize a quantity \( Q \) as: \( Q = 10^x \, Q_x \)
3 Discussion

We have shown that the early afterglows of GRBs are better suited for the study of the properties of the IGM at cosmological distance than any other known class of objects. GRBs, in fact, have at the same time a high luminosity, which makes them easy to detect and to study, and a small number of emitted photons, so that their presence do not influence the properties of the surrounding medium. They are therefore ideal probes, with the smallest possible impact on what we want to measure. Yet, they are very bright. It is fair to say that it is still unknown whether or not GRBs emit Lyman–α line radiation. What we have shown here is that, should such a line be observed in a GRB spectrum, this would imply $z_{\text{GRB}} < z_{\text{Reion}}$, while this is not true for QSOs.

This set of good properties is possible thanks to the fact that GRBs are transient phenomena. For this reason, we must be able to detect and follow up them in real time in order to fully exploit all the information they carry. In particular, it is important to select the high redshift bursts as soon as possible in order not to waste too much telescope time on nearby objects. This can be done through prompt NIR imaging, by the Lyman drop–out technique. For this reason, robotic IR telescopes are planned to complement the foreseen SWIFT mission (see, in particular, Zerbi et al. 2001).

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