GRB Progenitors and environment(*)

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Summary. — The study and knowledge of the environment of Gamma-Ray Bursts is of great interest from many points of view. For high redshift ($z > 0.5$) events, the structure of the ambient medium is one of the best indicators of the nature and properties of the progenitor. It also tells us about the last stages of the pre-explosion evolution of the progenitor. In addition, it is interesting in its own as a sample of the interstellar medium in a high redshift galaxy. Measures of the density and structure of the GRB environment are however sparse, and different methods yield different, often incompatible, results. I will review the methods and results with particular emphasis on the case of GRB 021004, a puzzling but highly informative event. I will finally underline the advancements that will be possible in the Swift era.

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1. – Introduction

The medium surrounding the location where a Gamma-Ray Burst (GRB) exploded has become an issue of study since the detection of the first afterglows. In fact, it is thanks to the absorption features imprinted by the ambient medium on the afterglow spectrum of GRB 970507 that the first GRB redshift was ever measured [1]. Absorption measurements, however, usually allow us only to infer the column density of the material lying along the line of sight to the observer and not its structure and geometry.

Modeling of the afterglow light curve is a tool that can be used to infer the environment structure in the surroundings of the GRB, up to a distance of several tens of parsec to several parsec, *i.e.* the distance traveled by the relativistic fireball before becoming sub-relativistic. The largely heuristic nature of the afterglow theory prevents us from drawing consistent results from the method. Alternative methodologies involve either
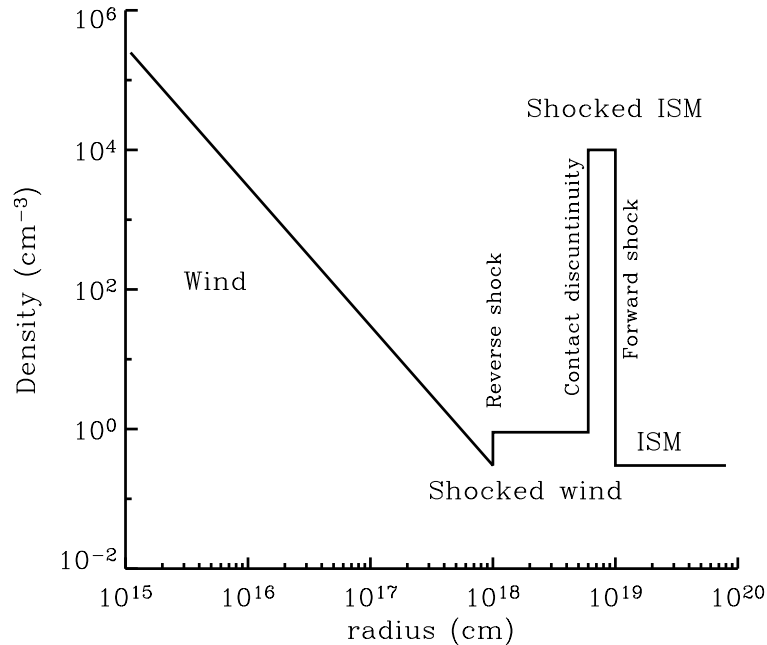
Fig. 1. – Schematic view of the density structure in a simple case of wind-ISM interaction [7].

reverberation techniques or time variability of the opacity of the surrounding medium to constrain certain properties of the environment.

In this contribution I will review the techniques used to measure the environment properties of cosmological GRBs and discuss the results obtained. I will focus on the discrepancy in the results of different approaches and discuss what Swift, with its rapid follow up, will enable us to derive.

2. – Theory

The properties of the GRB close environment heavily depend on the object that is assumed to be the burst progenitor. It is now widely accepted that long GRBs are associated to the explosions of massive stars [2-4]. More uncertain, on the other hand, is the nature of the short burst progenitor. This is due to the lack of afterglow observations for short GRBs.

2˙1. *Wind profile*. – The association of long GRBs with massive star progenitors calls for a structured environment, at least in the close vicinity to the explosion site. Massive stars, and especially the Wolf-Rayet (WR) stars supposed to be progenitors of long GRBs, produce heavy and fast winds, which generate a decaying density profile of the form:

$$(1) \qquad n = 3 \times 10^{13} \, \dot{M}_{-5} \, R_{11}^{-2} \, v_8^{-1} \, \text{cm}^{-3}$$

where ([1]) $\dot{M}_{-5}$ is the mass loss rate in units of 10^{-5} solar masses per year and v_8 the wind terminal velocity in units of $10^8\,\mathrm{cm\,s^{-1}}$. Such profile is however only a first approximation to the environment of the massive stars. Several complications still awaits to be fully understood:

- the mass ejection rate of a star less than ~ 100 years to explosion may be far from constant, and so big deviations from the R^{-2} profile could be present;

- the wind of WR stars is observed to be clumped [5, 6];

- the interaction of the wind with the surrounding material generates a shock structure at radii of the order of parsecs.

Some work has been devoted to the last aspect, since the transition from a wind-dominated environment to the shock-shaped one and eventually to the molecular cloud should be at distances from the progenitor where the afterglow radiation is produced. In the simplest case, the transition should consist of a contact discontinuity between the wind material and the interstellar medium (ISM) and by two shocks (see fig. 1). A forward shock propagates out in the ISM while a reverse shock propagates backward in the Wind, creating a region of hot wind material with uniform density [7]. This uniform region is interesting for observations (see below). Its extent may very dramatically depending on the wind and ISM properties and, in some cases of high wind power, the shock can bounce back on the star wind and create a wide uniform hot region [8]. Going from 1-D to 2-D and 3-D models adds the complication of turbulence and clumping to the picture [9].

Another important aspect of wind theory that is not entirely clear is where from the wind starts. In other words, should the wind start immediately at the surface of the star, the Thompson opacity would be

$$(2) \qquad \tau_T = \frac{2}{R_{11}}\,\dot{M}_{-5}\,v_8^{-1}.$$

Since the radius of the progenitor star is constrained by simulations to be $R_\star \leq 10^{11}\,\mathrm{cm}$ [10], for fiducial mass loss histories and wind speeds, an optically thick environment would be expected. This would create strong effects due to the interaction of the primary photons with a dense medium.

2.2. Uniform ISM. – More uniform interstellar media are favored by different classes of progenitors. The main alternative to massive stars, and leading candidate for short GRB progenitor, is the merger of a binary system made of two compact objects. Such binary systems are long lived and, due to SN kicks, they travel outside their formation site and possibly out to the intergalactic medium. The fact that most long GRB afterglow observations favor this scenario is still a not entirely understood aspect of the problem.

2.3. Photon-ISM interaction: pairs. – An important effect of the propagation of γ-ray photons in the ambient medium is that a fraction of these photons are Thompson-scattered by the electrons. Scattered photons are ideal target for photon-photon interactions to give electron-positron pairs:

$$(3) \qquad \gamma + \gamma = e^+ + e^-$$

([1]) Here and in the following we will adopt the notation $Q_x = 10^x\,Q$ and will use cgs units, unless specified.

The problem can be dealt with if the ambient medium is optically thin [11]. The main consequence of the pair enrichment is that in the early afterglow the typical synchrotron frequency is small (since the same energy is divided into many more leptons). The early afterglow should therefore be optically dominated [12] (rather than X-ray).

2˙4. *Photon-ISM interaction: dust*. – At later times and larger radii ($r > 10^{16}$ cm), the energy and flux of photons is not large enough to produce pairs. Still, the photons interact with the environment and modify it. Let us first consider dust particles. Dust grains absorb photons mostly in the UV and soft X-ray band. Absorption results mostly in heating of the grain. If the heating is larger than the cooling rate (which is mostly radiative), the internal agitation of molecules becomes larger than the binding energy and the grain evaporates [13, 14]. Higher energy photons, instead, ionize the ion until a surface potential larger than the binding energy is created. At this point the ion may either break into pieces [15], in a runaway dissociation, or eject charged ions to re-establish equilibrium [14]. In the first case, the dust destruction can be effective to large radii, out to tens of parsec. In the second, more conservative, estimate, the dust distribution is affected out to large radii, but dust grains are completely destroyed only at smaller radii (out to ~ 10 pc at most).

2˙5. *Photon-ISM interaction: ions*. – Besides the interaction with dust grains, photons strongly interact with atoms and ions. The main effect of this interaction is the photoionization of the elements in the gaseous phase. What makes this process interesting to GRB environment studies (as well as the dust interaction discussed above) is that the photoionization is observed "live on stage", and as a consequence the column density of absorber can be observed to decrease in time [16-20]. Since the timescale with which the species are ionized grows with the square of distance, the timescale with which the column density decreases give us constraints on the distance of the absorber. Coupling this with the early time column density we can derive an average density as well.

2˙6. *Reverberation*. – It is in principle possible to derive the overall structure and density of the ambient medium by studying the reverberation of primary photons scattered or reprocessed by ions. These studies were triggered by the tentative detection of X-ray lines in the early afterglow of GRBs [21-23]. Unfortunately, such detections have never been confirmed, and so the results on the environment [24, 25] (very high densities in the close vicinity of the burster) are still to be considerate tentative.

3. – Observations

In this section I will summarize the observational results that have been obtained by applying the techniques described above to afterglow observations.

3˙1. *Afterglow modeling*. – The first estimates on the density and radial structure of the GRB ambient medium were derived by multi-wavelength and multi-epoch modeling of the afterglow intensity [26]. The afterglow model has four main unknowns: the density of the ISM, the energy of the fireball and the two shock parameters ϵ_e and ϵ_B. On the other hand, there are four observables: the three break frequencies (self-absorption, peak and cooling) and the normalization. For this reason the system of equations can be inverted to derive a solution. Generally, these analyses [27] yield preferentially uniform low-density environments, in striking contrast with the prediction of the collapsar progenitor model [28].
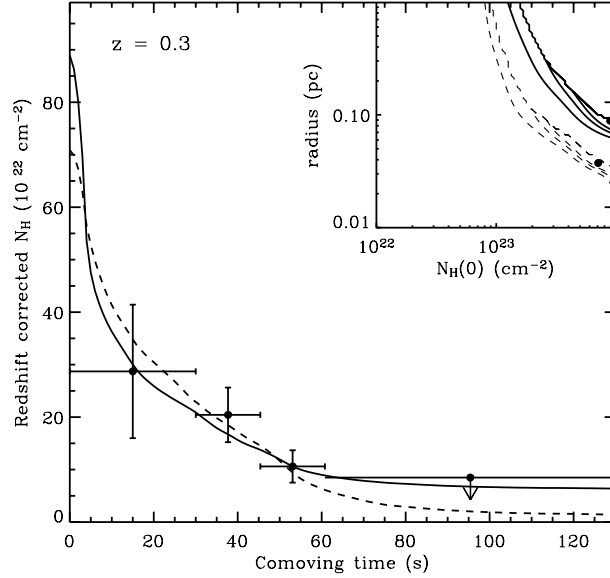
Fig. 2. – Column density measurements for GRB 000528 [31]. The solid and dashed lines are models of column density evolution for a uniform cloud and a shell surrounding the burst site, respectively. The inset shows the χ^2 contours and best fit parameters for the two cases.

The discrepancy could be due to oversimplification in the afterglow model [29] or to neglecting the effect of long lasting energy input from the inner engine [30]. Future observation will hopefully clarify this issue.

3˙2. *X-ray absorption.* – Several constraints have been obtained by modeling time-dependent X-ray absorption detected during the prompt phase of *Beppo*SAX GRBs. In some bursts the absorption in the soft X-ray continuum is observed to decrease in time, as predicted by the progressive photoionization of the environment (see fig. 2). Even though the data are not of sufficient quality to derive the radial structure of the absorber, the observations can be reproduced only if a high density compact absorber surrounds the GRB site [19,31] ($n \sim 10^6 \, \text{cm}^{-3}$; $r \sim 0.1 \, \text{pc}$).

In two other bursts, instead, a narrow absorption feature was observed to weaken in time. The best case is that of GRB 990705 [32]. A narrow absorption feature corresponding to the fully ionized K_α absorption edge of iron is detected only in the first ~ 10 seconds of the observation. The inferred amount of iron required to produce such a feature is huge (more than 100 solar masses). If the feature is considered to be due to resonant scattering from outward moving iron [33], a more reasonable amount of iron is required. Again, this detection points to a high density $n \geq 10^{10} \, \text{cm}^{-3}$ in close vicinity to the burst ($r \sim 0.01 \, \text{pc}$). An analogous feature was detected in GRB 011211 [34], yielding similar constraints, even though a faster outflow of the absorber was implied.

3˙3. *Optical resonant lines & GRB 021004.* – A more recent development has been possible thanks to the rapid and extended spectroscopic follow-up of GRB 021004. This GRB had a complex absorption system in its optical spectrum, characterized by the presence of multiple absorbers with different velocities, spanning a range of $\sim 3000 \, \text{km s}^{-1}$
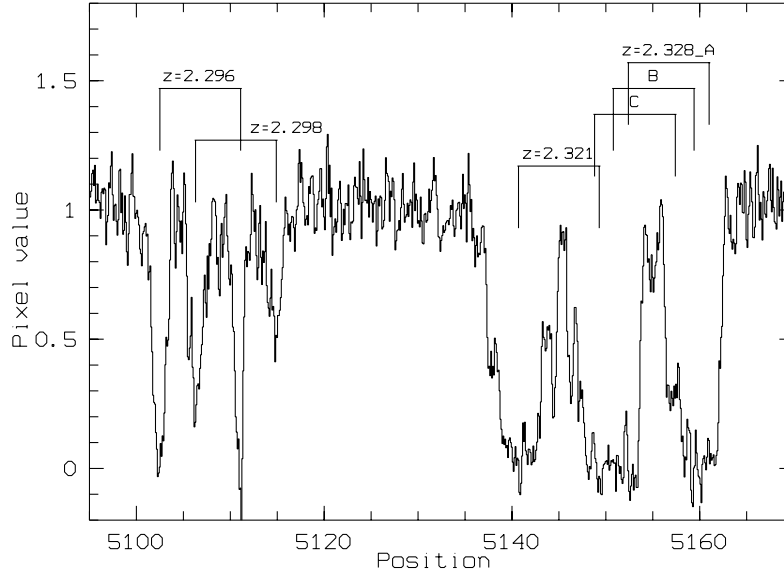
Fig. 3. – The complex CIV absorption system in the spectrum of GRB 021004 [35].

in proper speed (see fig. 3). The absorption systems were observed repeatedly in time from few hours to several days after the burst expolsion. This allows to derive the time evolution of the absorption for two elements: CIV and SiIV. Adopting a time dependent photoionization and dust destruction code [14] it is possible to model the evolution (or non-evolution) and derive limits on the distance and density of the various absorption systems. The results of this modelling are shown in fig. 4. The absence of a strong evolution of the equivalent widths of the lines with time requires a large distance for the absorber, of the order of tens of parsecs (^{2}). The density, however, is not well constrained [36].

4. – Summary and discussion

Figure 5 shows a graphic summary of all the available measurements of density of the GRB ambient medium, performed with different techniques that are sensitive at different distances. The size of the ellipses roughly represents the scatter of the measures for each method. While it is true that different techniques have been applied to different events, still the scatter is considerable and the agreement totally absent. The fact that X-ray based measurements are offset to higher densities does not surprises, since only if the (column) density is large something can be actually measured by its X-ray opacity. However, ten orders of magnitudes of difference in density with respect to afterglow modelling are quite big. The measurement performed in GRB 021004 [36] is roughly consistent with the afterglow density measurements. Unfortunately the high velocity of

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(^{2}) The actual best fit density depends on the model spectrum for the prompt γ-ray and optical flash emission. The figure shows a model with small optical emission.
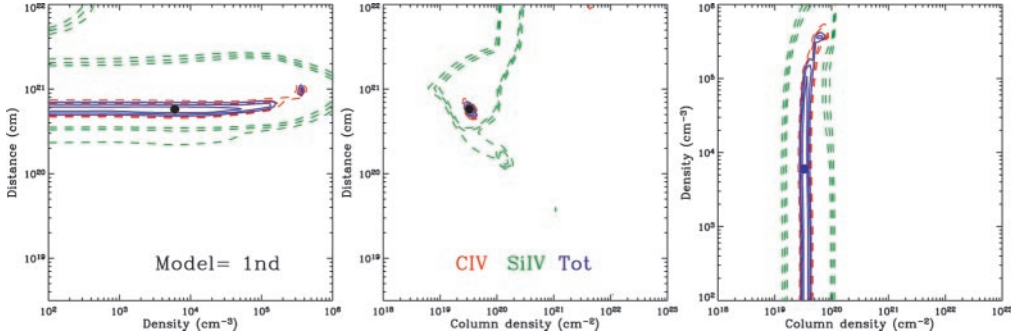
Fig. 4. – χ^2 contours in the density, column density and distance planes for the evolution of the column density if CIV and SiIV (dashed lines) in the spectra of GRB 021004. The solid line shows the combined contours. Levels are for 1, 2 and 3 standard deviations.

the lines calls for a wind profile, while consistency would be reached only in the case of a uniform medium.

The bottom line of fig. 5 is that what we still do not have a clear observational picture of what the circum-burst material looks like. Some observations may be circumstantial and some theory may need refinement.

In the Swift era this situation may change. Early observations will allow us to study in more detail the initial stages of the fireball-ISM interaction. This should allow us to better understand the physics of the reverse/forward shock and the importance of neutrons and pair enrichment. In addition, early observations are mandatory to study the clumpiness of the medium, since in the early stages only a small portion of the fireball is visible and therefore local properties of the ISM can be studied. Early photometry will
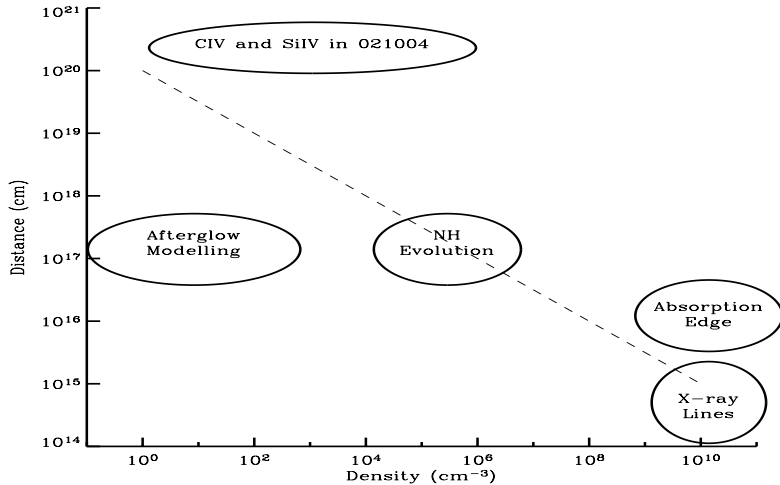

Fig. 5. – Summary cartoon of the average value of environment density measures performed with different techniques (and usually on different GRBs). The dashed line represents a wind profile.

also allow us to detect, if any, signatures of the dense environment close to a massive star, if the wind profile continues to the stellar boundary. Swift will also have a large impact on ground-based observations. Since photon-ISM interactions are stronger and faster at early times, prompt Swift localization will enablke us to study any time dependence in the opacity of the ISM. As discussed above, these are a powerful tool to study the radial profile of the absorber.

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REFERENCES

[1] METZGER M. R. *et al.*, *Nature*, **387** (1997) 879.
[2] GALAMA T. J. *et al.*, *Nature*, **395** (1998) 670.
[3] STANEK K. Z. *et al.*, *ApJ*, **591** (2003) L17.
[4] HJORTH J. *et al.*, *Nature*, **423** (2003) 847.
[5] SCHILD H. *et al.*, *A&A*, **422** (2004) 177.
[6] MARCHENKO S. V., GROSDIDIER Y., MOFFAT A. F. J., WOOD E. and ZIMMERMAN R., *AAS*, **202** (2003) 801.
[7] CHEVALIER R. A., LI Z. and FRANSSON C., *ApJ*, **606** (2004) 369.
[8] DWARKADAS V., *Talk at the INT workshop "Supernovae and Gamma Ray Bursts", June 21, 2004 - August 27, 2004.*
[9] VAN MARLE A. J., these proceedings (2005).
[10] ZHANG W., WOOSLEY S. E. and HEGER A., *ApJ*, **608** (2004) 365.
[11] BELOBORODOV A. M., *ApJ*, **565** (2002) 808.
[12] BELOBORODOV A. M., *ApJ*, **627** (2005) 346.
[13] WAXMAN E. and DRAINE B. T., *ApJ*, **537** (2000) 796.
[14] PERNA R., and LAZZATI D., *ApJ*, **580** (2002) 261.
[15] FRUCHTER A., KROLIK J. H. and RHOADS J. E., *ApJ*, **563** (2001) 597.
[16] PERNA R. and LOEB A., *ApJ*, **501** (1998) 467.
[17] BÖTTCHER M., DERMER C. D., CRIDER A. W. and LIANG E. P., *A&A*, **343** (1999) 111.
[18] LAZZATI D., PERNA R. and GHISELLINI G., *MNRAS*, **325** (2001) L19.
[19] LAZZATI D. and PERNA R., *MNRAS*, **330** (2002) 383.
[20] LAZZATI D. and PERNA R., *MNRAS*, **340** (2003) 694.
[21] PIRO L. *et al.*, *ApJ*, **514** (1999) L73.
[22] REEVES J. N. *et al.*, *Nature*, **416** (2002) 512.
[23] GHISELLINI G., LAZZATI D., ROSSI E. and REES M. J., *A&A*, **389** (2002) L33.
[24] LAZZATI D., CAMPANA S. and GHISELLINI G., *MNRAS*, **304** (1999) L31.
[25] LAZZATI D., RAMIREZ-RUIZ E. and REES M. J., *ApJ*, **572** (2002) L57.
[26] WIJERS R. A. M. J. and GALAMA T. J., *ApJ*, **523** (1999) 177.
[27] PANAITESCU A. and KUMAR P., *ApJ*, **571** (2002) 779.
[28] CHEVALIER R. A. and LI Z., *ApJ*, **520** (1999) L29.
[29] ROSSI E. and REES M. J., *MNRAS*, **339** (2003) 881.
[30] BJÖRNSSON G., HJORTH J., PEDERSEN K. and FYNBO J. U., *ApJ*, **579** (2002) L59.
[31] FRONTERA F. *et al.*, *ApJ*, **614** (2004) 301.
[32] AMATI L. *et al.*, *Science*, **290** (2000) 953.
[33] LAZZATI D., GHISELLINI G., AMATI L., FRONTERA F., VIETRI M. and STELLA L., *ApJ*, **556** (2001) 471.
[34] FRONTERA F. *et al.*, *ApJ*, **616** (2004) 1078.
[35] FIORE F. *et al.*, *ApJ*, **624** (2005) 853.
[36] FLASHER J. *et al.*, in preparation.