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A METAL-RICH MOLECULAR CLOUD SURROUNDS GRB 050904 AT REDSHIFT 6.3

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ABSTRACT

GRB 050904 is the gamma-ray burst with the highest measured redshift. We performed time-resolved X-ray spectroscopy of the late GRB and early afterglow emission. We find robust evidence for a decrease with time of the soft X-ray–absorbing column. We model the evolution of the column density due to the flash ionization of the GRB and early afterglow photons. This allows us to constrain the metallicity and geometry of the absorbing cloud. We conclude that the progenitor of GRB 050904 was a massive star embedded in a dense metal-enriched molecular cloud with $Z \gtrsim 0.03\ Z_{\odot}$. This is the first local measurement of metallicity in the close environment of a GRB and one of the highest redshift metallicity measurements. We also find that the dust associated with the cloud cannot be similar to that of our Galaxy but must be either sizably depleted or dominated by silicate grains. We discuss the implications of these results for GRB progenitors and high-redshift star formation.

Subject headings: dust, extinction — gamma rays: bursts — ISM: abundances — stars: formation

Online material: color figures

1. INTRODUCTION

The studies of the properties of the interstellar medium (ISM) at high redshift have traditionally relied on the observations of quasars, and most of our knowledge about the ISM metallicity comes from measurements of the absorption signatures of overdense gas along their lines of sight. However, such measurements are likely giving us a partial view of the properties of the high-redshift medium, as they are biased toward regions of low density (e.g., Bromm & Larson 2004). On the other hand, quasar spectra also show emission lines coming from dense gas in the immediate vicinity of the quasars themselves. They provide strong hints of an high metal content; for example, millimetric and radio observations of a CO line from the most distant quasar ($z = 6.4$) suggest the presence of large amounts of carbon and oxygen (Walter et al. 2003; Bertoldi et al. 2003). The main drawback of such measurements is that they necessarily probe only the high-luminosity end of the quasar luminosity function, whereas it is known that at low redshifts, the measured metallicity scales with luminosity (Pettini et al. 1997; Pentericci et al. 2002).

In order to have a more representative and comprehensive understanding of the properties of the ISM in high-redshift galaxies, a fundamental complement to studies performed with quasars comes from gamma-ray burst (GRB) studies (Fiore et al. 2005; Prochaska et al. 2006). GRBs are intense, short impulses of γ-rays occurring randomly in the sky. Their intense luminosity allows their detection up to the highest redshifts (in principle, $z \gtrsim 20$), outshining by orders of magnitude the one from quasars at similar distances. Long GRBs are associated with the death of massive stars (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004; Campana et al. 2006) and should occur in star-forming regions. This property, together with their power law and almost featureless spectra, make GRBs ideal probes of star-forming regions in the high-redshift universe. What particularly differentiates GRB sources from quasars as cosmological lighthouses is the fact that, being very bright and very short-lived, GRBs can alter the equilibrium state of their surrounding medium on an observable timescale by photoionizing gas (Perna & Loeb 1998) and destroying dust (Waxman & Draine 2000). These effects cause a gradual reduction of the opacity from the X-ray band (due to progressive ionization of the metals) to the optical band (due to the progressive destruction of the dust grains).

Here we use time-dependent X-ray spectroscopy to investigate the properties of the environment of GRB 050904 (Cusumano et al. 2006; Kawai et al. 2006), the farthest detected so far at a redshift of $z = 6.3$ (Tagliaferri et al. 2005; Kawai et al. 2006). We show that the burst most likely exploded within a rather compact H II region, produced inside a dense molecular cloud during the main-sequence life of the progenitor star. We also show that a substantial metal enrichment must have taken place before the formation of the progenitor star, pointing at the presence of a generation of massive stars at $z > 6$, even in objects of relatively low luminosity and mass like the GRB host galaxy (Berger et al. 2006).

2. *SWIFT* DATA

The *Swift* satellite (Gehrels et al. 2004) discovered GRB 050904 with its Burst Alert Telescope and repointed its X-ray and UV/optical telescopes within 161 s (Cusumano et al. 2006). Observations continued up to 10 days. Data were accumulated in Window Timing (WT) mode up to 534 s after the trigger and in Photon Counting (PC) mode later on (see Burrows et al. 2005a). Data were extracted using the latest software (HEAsoft ver. 6.0.4) and a standard (40 × 20 pixel) window for WT data and a circular (30 pixel radius) region for PC data. A small hole in the extraction region of 2 pixels has been used when the PC data showed signs of pileup.

The number of photons collected by the *Swift* X-Ray Telescope (XRT) was sufficiently high to allow us to perform time-resolved spectral analysis of the X-ray light curve of GRB 050904 (Cusumano et al. 2006; Watson et al. 2006; Gendre et al. 2006). Analysis was carried out in 0.3–10 keV for WT and PC modes.

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TABLE 1
Results of the Spectral Fit with Variable Absorption and Metallicity

Time Interval in the Rest Frame (s)	XRT Obs. Mode	Total Counts	N_H (10^{22} cm^{-2})			Power Law (Γ)
			$Z = 0.1\ Z_\odot$	$Z = 0.3\ Z_\odot$	$Z = Z_\odot$	
28.9 ± 6.9	WT	3674	$71.3^{+14.1}_{-14.1}$	$25.1^{+3.9}_{-4.6}$	$7.9^{+1.1}_{-2.1}$	$1.2^{+0.1}_{-0.1}$
49.5 ± 13.7	WT	4729	$66.5^{+7.5}_{-7.6}$	$23.3^{+3.0}_{-4.8}$	$7.3^{+1.4}_{-1.4}$	$1.5^{+0.1}_{-0.1}$
73.5 ± 10.3	WT	1532	$41.0^{+9.7}_{-10.3}$	$14.4^{+4.3}_{-3.8}$	$4.5^{+2.3}_{-1.1}$	$1.8^{+0.1}_{-0.3}$
4130.5 ± 4051.8	PC	4987	$15.4^{+3.7}_{-5.5}$	$5.3^{+2.1}_{-1.8}$	$1.8^{+0.7}_{-0.4}$	$1.6^{+0.2}_{-0.2}$
Probability[a]			1.6×10^{-10}	1.4×10^{-7}	3.2×10^{-6}	
Reduced χ^2 (nhp)[b]			1.00 (48%)	1.00 (48%)	1.00 (48%)	

Note.—Errors are at 1 σ confidence level ($\Delta\chi^2 = 1.0$).
[a] This probability has been estimated as the probability that a constant N_H model provides an acceptable fit to the data.
[b] We have 304 degrees of freedom in each fit. The null hypothesis probability (nhp) for each model is in parentheses.

Spectra are grouped to 30 counts per spectral bin. A systematic error of 3% has been added to cope with the uncertainties in the XRT response matrices. To describe the GRB spectra when flares are present, we adopted a power-law emission model with a high-energy cutoff (Burrows et al. 2005b; Falcone et al. 2006). We divided the XRT light curve into four time intervals and computed the equivalent column density with the above spectral model. Given the large number of X-ray flares (see Fig. 1 in Cusumano et al. 2006), we fit the spectra (three in the WT mode and one in the PC[6] mode) with different cutoff energies and power-law spectral indices. The contribution of our Galaxy to the absorption toward GRB 050904 can be estimated from H I maps as 4.9×10^{20} cm^{-2}. *IRAS* maps instead provide a lower value of 3.5×10^{20} cm^{-2}. We left the Galactic column density free to vary in the range $(3–5) \times 10^{20}$ cm^{-2} (using the model `tbabs`, within XSPEC). The absorption in the host galaxy was modeled with `zvfeabs` within XSPEC, setting the iron abundance to zero since at such an early time, it had likely not been produced yet (e.g., Prochaska & Wolfe 2002; allowing for the presence of iron would result in an inferred column density about 20% smaller). Finally, we fit the spectra, minimizing the gain shift in order to overcome small energy scale problems, especially relevant at low energies.[7]

[6] XRT response matrices for the two observing modes have been cross-calibrated on a stable X-ray sources without showing any major difference.

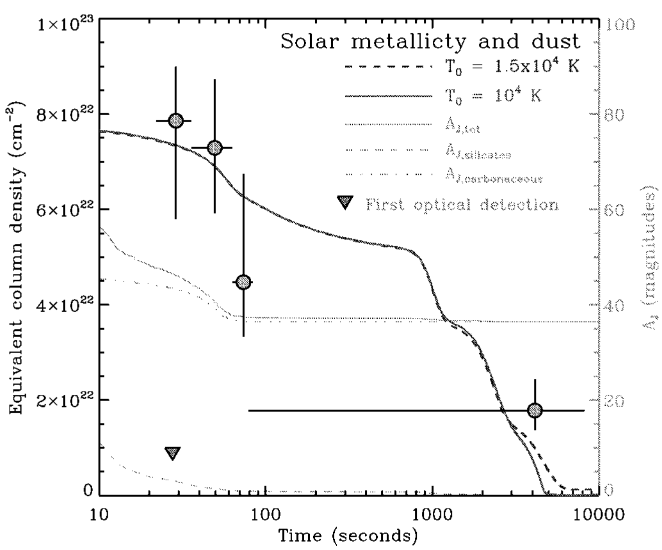

Fig. 1.—Evolution of the equivalent column density measured in the X-ray afterglow of GRB 050904 (gray circles with error bars at 1 σ). Time is in the rest frame. Solar metallicity with no Fe and Ni has been assumed. The equivalent column density is defined as the column density that would produce the same amount of absorption for a cold nonionized absorber. The thick solid line and the thick dashed line show the best-fit models (see Table 2) for different initial temperatures. The photoionization code has in input the observed light curve of GRB 050904 (Cusumano et al. 2006). The drop in absorption at $t \sim 1000$ s (in the rest frame) corresponds to the group of bright X-ray flares. The thin solid line (and right y-axis) shows the amount of absorption that would be observed in the J band (rest frame ~7.2 eV) if the X-ray–absorbing medium were polluted with Galactic-like dust (Mathis et al. 1977). The optical transient was observed at $t_{obs} = 200$ s (i.e., 27 s rest frame; Boër et al. 2006) in white light, indicating very little absorption. Thin dashed and dot-dashed lines show the absorption due to silicates only and to carbonaceous grains only, respectively. The little extinction implied by the early optical observation can be explained by a dust component rich in silicates and depleted in carbonaceous grains. This could be the results of an ISM enriched by pair-instability supernovae (Schneider et al. 2004). [*See the electronic edition of the Journal for a color version of this figure.*]

We considered three possible metal abundances (0.1, 0.3, and 1 $Z_\odot$, except of iron; see also below). We detect highly significant absorption in excess of the Galactic value. For all the considered metallicities, we find that the equivalent column density decreases with time at a high significance level (see Table 1 and Fig. 1; see also Watson et al. 2006, Boër et al. 2006, and Gendre et al. 2006). In particular, we note that the GRB spectrum gets softer as time passes (see Table 1). If the column density decrease is a spurious effect, one would expect an increase in the observed column density to be larger than the number of photons at low energies to be hidden. This is not the case, thus strengthening the observational result. This is consistent with the idea that the circumburst-absorbing material is photoionized by the high-energy photons of the burst. Among the very few GRBs for which opacity evolution has been detected, this is not only the first GRB at a known distance but also the first GRB at the largest distance known so far. This is not surprising since the cosmological time dilation allows us to observe the X-ray spectrum at small comoving times.

The data quality does not allows us to fit the metallicity as a free parameter. An upper limit on the initial column density of the material along the line of sight comes from the consideration that if it were larger than $1/\sigma_T = 1.5 \times 10^{24}$ cm^{-2}, the medium would be Thomson-thick and the prompt γ-ray radiation multiply scattered. This would introduce a variable delay between photons, attenuate the prompt emission, and smear the variability pattern, in contrast to the observations. By imposing a Thomson-thin medium at the time of the measurements, we obtain the constraint on the metallicity $Z \gtrsim 0.03\ Z_\odot$ (90% confidence level; see Fig. 1).

[7] See http://swift.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/xrt/SWIFT-XRT-CALDB-09.pdf; a more complete description will be presented in S. Campana et al. (2006, in preparation).

TABLE 2
Result of the Time-dependent Column Density Fits

$Z/Z_\odot$	$T(0)$[a] (K)	N_H[b] (10^{22} cm^{-2})	R (pc)	Mass ($10^4\ M_\odot$)	χ^2 (Prob.)[c]
0.1	10^4	64 ± 12	1.2 ± 0.3	$9^{+3.5}_{-1.5}$	1.4 (50%)
0.3	10^4	23^{+9}_{-5}	1.8 ± 0.7	9 ± 5	1.2 (55%)
1.0	10^4	7.7 ± 1.5	3.2 ± 0.6	12 ± 3	0.86 (65%)
	1.5×10^4	7.7 ± 1.1	4.7 ± 0.9	24 ± 6	0.79 (67%)

Note.—Errors are at 1 σ confidence level for one parameter of interest ($\Delta\chi^2 = 1.0$).
[a] Initial temperature of the gas before the GRB explosion.
[b] N_H is the column density of hydrogen irrespective of ionization $N_H = N_{H\,I} + N_{H\,II}$.
[c] For the fits with 2 degrees of freedom. The null hypothesis probabilities are in parentheses. Given the quality of the fits, they are all statistically acceptable.

3. PHOTOIONIZATION STUDY

The propagation of the photons through the cloud surrounding the GRB alters the local thermal equilibrium conditions. The gas ionization state and dust content will then depend on the time from the burst onset and the distance from the burster. The optical depth of the medium, which is obtained by radial integration of the local opacity at a given time, can be computed only numerically (Perna & Lazzati 2002). Here we use a time-dependent photoionization and dust destruction code that can take into account any light curve, metallicity, and dust content (Perna & Lazzati 2002). It allows us to simulate how the conditions in the environment of GRB 050904 vary as a result of the burst radiation. Inputs of the code are the total hydrogen column density (irrespective of its ionization state) and the geometry of the absorber, which we assume to be a shell at distance R from the burst site and width $\Delta R = 0.1R$. The choice of fixing the shell width is due to the consideration that the density of the absorber is irrelevant, due to the fact that the recombination times are much longer than the observed times. The fit results are reported in Table 2. We find that the absorption and its evolution can be explained by a GRB surrounded by a shell of material with a radius of a few parsecs and a high column density $N_H \sim 7 \times 10^{22}/(Z/Z_\odot)$ (see Fig. 2). This is consistent with X-ray spectral fitting data (see Fig. 1), and it implies a total mass of the absorber of $M \sim$ few $\times$ $10^5\ M_\odot$ and a total mass of metals (excluding He) of about 10^2–$10^3\ M_\odot$. Higher metallicities imply larger radii and therefore larger metal masses. In all cases, the fits have an acceptable value of χ^2 (associated probability larger than ∼50%). We also explored the role of the initial gas temperature. We find that for initial temperatures $T_0 < 10^4$ K, the fits are indistinguishable. If the initial temperature is instead above 10^4 K, H II starts to become relevant, and the best-fit radius moves outward. The column density is instead unaffected.

These results allow us to infer the origin of the absorbing medium. It must be located in the close vicinity of the GRB progenitor, and so it could be either the molecular cloud where the progenitor star formed or the material ejected from the stellar progenitor during its evolution, in the form of a wind or of a massive ejection event. However, the mass of the absorber is too large to be the result of ejection from a single stellar progenitor (not even from a massive Population III star). We conclude that the progenitor of GRB 050904 formed within a molecular cloud enriched with metals. In support of our interpretation, Frail et al. (2006) found a density of ∼700 cm^{-3} at a distance of ∼1 pc from the burster from the modeling of the radio afterglow, while Kawai et al. (2006) and Totani et al. (2006) found a density of $n \sim 200$ cm^{-3} at a distance larger

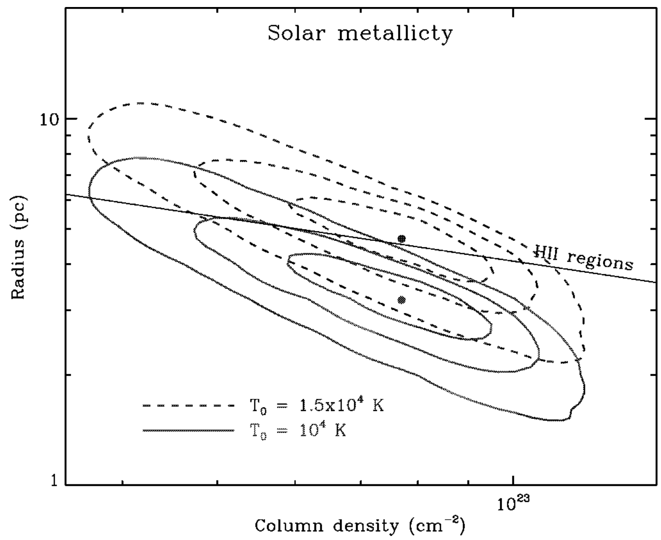

Fig. 2.—Confidence contour (1, 2, and 3 σ) in the radius–column density plane for the solar metallicity case. The computed grid of radii and column densities over which the fit was performed is much larger and spans 10^{16} cm $< R < 10^{21}$ cm and 10^{21} cm$^{-2} < N_H < 10^{25}$ cm^{-2}. The black line shows the locus of H II regions surrounding massive stars at the end of their life under the assumption of uniform density of the progenitor molecular cloud. Despite the simple model, the agreement is satisfactory. [*See the electronic edition of the Journal for a color version of this figure.*]

than several tens of parsecs from fine-structure lines in the Si II absorption. In Figure 2 we overlay the locus of H II regions produced by massive stars on the probability best-fit contours. We find that the properties of the best-fit region resemble those of an H II region, especially in conditions where most of the H is ionized ($T_0 = 1.5 \times 10^4$ K). The high-temperature simulation also shows a residual H I column that could explain the late-time observation of $N_{H\,I} \sim 4 \times 10^{21}$ cm^{-2} in the optical spectrum several days after the explosion (Totani et al. 2006) in the case of a molecular cloud with roughly solar composition.

Optical–to–near-infrared observations detected the afterglow, resulting in a rest-frame observation in the ultraviolet (Tagliaferri et al. 2005; Haislip et al. 2006; Boër et al. 2006). Photometric redshift codes were successful in recovering the spectroscopic redshift without the addition of local reddening. In order to detect this optical emission, we require the almost complete absence of dust absorption. Given the large amount of matter along the line of sight, this is not straightforward. A Galactic-like dust component (Mathis et al. 1977) is only partially destroyed by the GRB high-energy photons, resulting in an absorption of $A_J \sim 46$ mag at the time of the first optical observation (see Fig. 1). The residual absorption is almost entirely due to carbonaceous grains (see the dot-dashed line in Fig. 1). Therefore, the lack of absorption should be the result of the GRB environment having been enriched primarily by pair-instability supernovae, which are expected to produce mainly silicate dust grains (Schneider et al. 2004; see also Todini & Ferrara 2001). This is not unreasonable, because the star formation rate of ∼15 $M_\odot$ yr^{-1} given by Berger et al. (2006) implies that pair-instability supernovae should be occurring at a rate of 0.01–1 yr^{-1}.

4. CONCLUSIONS

Optical and radio observations of the afterglow of GRB 050904 showed that it is likely embedded in a dense environment with relatively high metallicity (Kawai et al. 2006; Berger et al. 2006). We have analyzed the *Swift*-XRT X-ray data of GRB 050904. Time-resolved spectroscopy of the burst and afterglow reveals a very high column density at early times. The absorption decreases at later stages, almost disappearing $\sim 10^4$ s after the explosion. This behavior can be understood if the absorbing material is located very close to the GRB, so that the flash ionization of the environment progressively strips all the electrons off the ions, decreasing the opacity of the medium. We model the evolution of the opacity by simulating the flash ionization and dust destruction numerically with our time-dependent code (Perna & Lazzati 2002). We constrain the geometric properties of the environment, finding that GRB 050904 exploded within a dense metal-enriched molecular cloud. The nearby environment must have a metallicity of at least several percent solar. Such a metallicity is not due the burst progenitor but is a property of the whole cloud. We also find that most likely the immediate surroundings of the GRB were shaped like an H II region by the UV flux of the progenitor star. This result is consistent with the metallicity estimate derived from optical studies (Kawai et al. 2006; Totani et al. 2006), with a metallicity of $\sim 0.1\ Z_{\odot}$ based on S II lines. This should provide a fair description of the metallicity since sulphur is not depleted to dust grains.

Our results confirm, albeit in an indirect way, that even the highest redshift GRBs are associated with the death of massive stars. The metallicity constraint, the first derived for the molecular cloud where the burst exploded rather than for the host galaxy as a whole, shows that GRB progenitors can have relatively high metallicity.

From a cosmological point of view, our result shows that metal enrichment had already taken place at redshifts larger than 6. We also find that, for the derived abundance of metals, the absorber does not show any evidence of dust extinction. In the Galaxy environment, a UV extinction of several tens of magnitudes would be associated with such a high column density. We find that the GRB radiative heating would not have been enough to evaporate all the dust. The lack of UV extinction can be due to a strong underabundance of dust grains with respect to our local environment. Such an explanation seems unlikely given the availability of metals and their supernova origin (Todini & Ferrara 2001; Sugerman et al. 2006). We find that a possible alternative explanation is a dust mixture biased toward silicate grains, which are more easily destroyed by UV heating. In this case, the flash ionization of the GRB would reduce the UV extinction to low levels. Metal and dust enrichment due to a top-heavy initial mass function (possibly dominated by pair-instability supernovae) could explain the silicate-rich dust mixture (Schneider et al. 2004).

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