computed [36] for intermediate situations where both radiation damping and Doppler broadening must be considered, giving a “Voigt profile” instead of the simpler Maxwellian.

We turn now to the observations of narrow interstellar absorption lines. The extensive ground-based data on interstellar Na I and Ca II absorption provide information on the velocity distribution of the interstellar gas [35]. Many separate components are seen in these lines, with radial velocities for some Ca II components as high as 100 km s\(^{-1}\). The strongest components, with velocities up to about 10 km s\(^{-1}\) in the local standard of rest, generally correlate reasonably well with 21-cm emission components, but for the clouds of higher velocity the correlation is poor, with often no 21-cm emission observable at the velocity of a Ca II cloud. If a correction is made for blending, the number \(k\) of components per kpc has been estimated as between 8 and 10 [37], and with more recent higher resolution [38, 39] the number of components has been somewhat increased. Most of these components have presumably much less material in the line of sight than the absorbing H I clouds with \(\tau_1 > 0.2\), for which a value of 4 per kpc was obtained above for \(k\). If the clouds with weak Na I absorption are excluded, the dispersion \(\sigma_v\) of radial velocities between different clouds is about the same 6 km s\(^{-1}\) [29] obtained from the 21-cm data.

The effective thickness \(2H\) of the gaseous galactic disk has been obtained [40] from the measured \(W_\lambda\) of the K line of Ca II at 3933.7 \(\AA\). Since this line is relatively unsaturated, \(W_\lambda\) is nearly proportional to \(N(Ca\ II)\). Dividing \(N(Ca\ II)\) for a line of sight through the Galaxy, pole to pole, by the mean \(n(Ca\ II)\) in the galactic plane gives \(2H = 240\) pc, in good agreement with the value obtained from 21-cm emission [53.3b]. Some clouds producing measurable Ca II absorption are at much greater distances from the galactic plane; on the average, a line perpendicular to this plane intersects from 0.25 to 0.5 such clouds beyond 750 kpc and with a radial velocity exceeding 24 km s\(^{-1}\) [41].

The composition of several H I clouds has been determined [34] from measures of \(W_\lambda\) for many lines, mostly in the ultraviolet. The most detailed results are for the line of sight to \(\delta\) Oph (\(E_{B-V} = 0.32\)). A few of the interstellar lines in this star, including some lines of the dominant singly ionized atoms of Mg, P, Ni, and Fe, are on the linear part of the curve of growth, giving column densities directly from the adopted \(f_\lambda\). For other lines a curve of growth must be used. Since there is no reason to expect that \(\phi_c(\Delta v)\) is Maxwellian, the theoretical curve of growth discussed above is not necessarily realistic. It is necessary to construct empirical curves of growth, combining in one group those atoms which might be expected to show the same mean velocity distribution function. For example, atoms of the dominant ionization species in H I regions, such as Ni I, O I, Mg II, and Si II, would be expected to have the same \(\phi_c(\Delta v)\), provided that their relative abundances were the same in all clouds. However, neutral atoms such as Mg I and Si I, whose relative abundances should be proportional to the density, will have different abundances relative to their corresponding ions in different clouds and consequently a different \(\phi_c(\Delta v)\) from that of Mg II and Si II. Within each group the values of \(\log(W_\lambda/\lambda)\) from a variety of lines absorbed by a particular atom can be plotted against \(\log(\lambda)\) to give a section of the curve of growth. Different sections are then shifted horizontally to agree with corresponding sections found from other atoms in the same group; \(N_\lambda\) is then determined from lines on the linear section. Figure 3.2 shows the empirical curves of growth obtained in this way for \(\delta\) Oph, indicating the difference between different groups of elements; for the triangles, representing Mg I, Si I, and neutral atoms of similar elements, the curve of growth clearly does not correspond to the theoretical curves for a Maxwellian \(\phi_c(\Delta v)\), but it may be reproduced by several clouds with different radial velocities and widely different column densities.

Figure 3.2 Curves of growth for interstellar lines in \(\delta\) Oph [34]. The filled circles represent lines produced by Al I, Ar I, Mg II, Si II, and Fe II, representing for each element the dominant stage of ionization in an H I region. The triangles represent C I, Na I, Mg I, Si I, K I, and Fe I; these are neutral atoms of elements which are mainly singly ionized in H I regions. The crosses represent H2 Lyman lines from the levels with rotational quantum number \(J\) between 2 and 6. The two solid lines represent theoretical curves for a Maxwellian velocity distribution with the indicated values of \(b\), equal to \(2^{1/2}\) times the dispersion of radial velocities.
Regardless of whether the grains were born in stellar atmospheres or in dense interstellar clouds, the depletion found for different elements seems consistent with a relatively simple model of grain formation in a gas of decreasing temperature and density [16]. On this model, the elements with the highest condensation temperature $T_c$ should condense first, with other elements condensing later. If the density decrease is sufficiently rapid, the fraction of atoms of each element condensing into grains will be less for the low-$T_c$ elements than for those of high $T_c$. Figure 9.1 shows a plot of the depletion observed [17] in the interstellar cloud in the line of sight to $\xi$ Oph [S3.4c]; the values of the depletion given in Table 1.1 are plotted against computed values of $T_c$ [16]. In the computations, the gas with a temperature $T$ is assumed to have cosmic composition and to be at a pressure of about 1000 dyne cm$^{-2}$. The abundances of the different molecular species are determined by the appropriate relations for thermodynamic equilibrium. The value of $T$ at which half the atoms of a given element have condensed out in one form or another is defined as $T_c$. At different pressures, the values of $T_c$ are different, but the general appearance of the plot in Fig. 9.1 is not much changed. There seems no question but that the depletions tend to be large for the elements of highest $T_c$.

One might expect that small grains composed of the more refractory materials (characterized by higher melting temperatures) might form first from condensation in a relatively dense cloud, and that mantles of CH$_4$, NH$_3$, and H$_2$O would form at a later time, perhaps within the denser observed diffuse clouds. The depletion of C, N, and O shown in Fig. 9.1 is somewhat uncertain, but is consistent with the apparent observed increase in grain radius with $E_{-\nu}$ in extended cloud complexes [S8.2b]. Also consistent with this point of view is the relatively slight depletion observed for N and O in more transparent clouds [S3.4c].

While the theory of initial grain condensation in a dense warm gas yields some impressive agreement with the observations, the model raises certain difficulties. The very large depletion of elements such as Ca and Ti seems easily understood if all the atoms of these elements have passed through this condensation phase. However, it is generally assumed that the atoms of these heavy elements were formed in supernovae rather than in late-type giants; it seems unlikely that almost all the heavy elements in interstellar space have passed either through stars or through dense high-temperature interstellar clouds at least once since being ejected from supernovae. In addition, the agreement shown in Fig. 9.1 is about as good if the depletion is plotted against first ionization potential, provided that the three alkali metals, Li, Na, and K, are arbitrarily excluded [18].

If one assumes that the condensation nuclei have formed somehow, the rate at which the grains grow by accretion in observed diffuse clouds can be computed on the basis of a relatively simple model. For grains with more than a certain number of atoms, one might expect that the sticking probability $\xi$ for most atoms would be not far below unity. Physical adsorption to the surface, which requires no activation energy, should be possible, and an atom colliding with the grain is likely to give up enough of its kinetic energy so that it will become bound. Detailed analysis [19] confirms that $\xi \approx 1$ for neutral atoms, although important uncertainties remain for $C^+$ and other positive ions.

We compute now the rate at which the grain radius $a$ will grow by this accretion process. If $m_a$ denotes the mass of the grain, while the particle density, mass, and velocity of the colliding atoms are denoted by $n_a, A_m$, and $v_a$, respectively, and if the loss processes considered below are ignored, the rate of mass accretion by the grains becomes

$$\frac{dm}{dt} = \pi a^2 \nu_a n_a A_m \xi_a,$$

(9-28)
HEAVY-ELEMENT ABUNDANCES AND DUST DEPLETIONS IN THE HOST GALAXIES
OF THREE GAMMA-RAY BURSTS

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ABSTRACT

We have derived the column densities of heavy elements in three gamma-ray burst (GRB) optical transients, associated with the circumburst or interstellar medium (ISM) of the host galaxy. In comparison with the same elements observed in damped Lyα (DLA) systems along QSO sight lines, we find evidence for much higher column densities of Zn ii. The gap between the QSO-DLA and GRB-DLA distributions is smoothly bridged by observations of the interstellar absorption in the Milky Way and the Magellanic Clouds. Very small [Fe/Zn], [Si/Zn], and [Cr/Zn] values in GRB-DLAs indicate large dust depletions. Once the dust-to-metals ratios are determined, we find an optical extinction \(A_V \approx 1\) mag, to be compared with typical \(A_V \lesssim 0.1\) in most QSO-DLAs. Our inference of high dust content appears to be in contradiction with the typical low reddening previously found in GRBs. One possible way to reconcile is a dust grain size distribution biased toward big grains, which would give a gray extinction. Possibly, the small dust grains have been destroyed by the GRBs themselves. Our findings support the idea that primarily optically selected QSOs probe locally high-gas/dust regions of high-redshift galaxies, while the more powerful GRBs can be detected through denser regions of their ISM (molecular clouds and star-forming regions). Therefore, GRB-DLAs and QSO-DLAs together provide a more complete picture of the global properties of the interstellar medium in high-redshift galaxies.

Subject headings: cosmology: observations — dust, extinction — gamma rays: bursts — intergalactic medium — quasars: absorption lines

On-line material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are among the most dramatic events in the universe. Their luminosities are so high (\(10^{51} - 10^{54}\) ergs are emitted in a few seconds) that they can be seen at the highest redshifts. However, since the decline in their energy emission is very fast, the investigation and understanding of their physical nature is not particularly easy (Piran 2003). For instance, the redshift of the afterglow or host galaxy has been measured in only 24 cases.\(^2\)

Only eight of these objects have been targeted quickly enough by ground-based telescopes to obtain low-resolution spectra of the optical transient, and all show a common peculiarity: very strong UV absorption lines of low-ionization species (Fiori 2001; Fynbo et al. 2002). This is similar to what is seen in damped Lyα systems (DLAs) associated with intervening galaxies along QSO sight lines. GRB-DLAs are certainly an unexplored and important source of information about the intergalactic medium (ISM) of the GRB host galaxy. Here we explore in more detail their properties and compare them with those of QSO-DLA galaxies.

We use the curve-of-growth (COG) analysis to derive column densities of low-ionization species in several GRB-DLAs. As for QSO-DLAs, we neglect ionization effects to derive the abundances of several heavy elements. The low ionization of the gas is warranted by the large equivalent widths of the low-ionization lines and the low equivalent widths of the moderate- and high-ionization lines. The difference in abundances between weakly and greatly dust-depleted elements provides an estimate of the dust content.

The COG analysis was applied to QSO-DLAs (Blades et al. 1982; Turnshek et al. 1989) before the advent of high-resolution spectroscopy, which allows a direct fitting of individual absorption lines. Since GRB emission fades very rapidly, high-resolution (FWHM \(\sim 10\) km s\(^{-1}\)) spectra of GRB afterglows are very hard to obtain.

In this work, we interpret strong differences between GRB-DLAs and QSO-DLAs as the result of the difference in the densities of the intervening gas. Since GRBs are at least for some time, brighter than primarily optically selected QSOs, they can be observed even if their sight lines cross very dense and dusty regions, such as molecular clouds, where extinction is very severe. On the other hand, QSO sight lines are easier to detect when intersecting less dusty interstellar clouds.

This bias in QSO-DLAs has been already suggested in the past (see, e.g., Fall & Pei 1993; Boisso et al. 1998). More recently, Ellison et al. (2001) have studied a small sample of

\(^1\) On leave of absence from Osservatorio Astronomico di Roma, Italy.

\(^2\) See http://www.mpj.mpg.de/~jcg/grbgen.html for the complete list of GRB redshifts.
radio-selected QSOs and tentatively found more DLAs than in optically selected QSOs. Even if this result is affected by small number statistics (significant at ~2σ level), it supports the idea of dust obscuration in optically selected QSO-DLAs.

Our analysis is alternative to and independent of the dust content estimate obtained so far for GRBs. The dust reddening in GRB afterglows has been derived in several objects (see, e.g., Reichart 1998; Jensen et al. 2001; Roahs & Fruchter 2001; Fynbo et al. 2001; Galama & Wijers 2001), and in most cases it has been found to be small or negligible. The method applied assumes initial power-law emission from the GRBs and steep extinction curves such as those in the Milky Way (MW) or Large and Small Magellanic Clouds (MCs). Possible discrepancies with the results of our analysis challenge the two initial assumptions of very steep extinction and initial power-law emission of the central source.

For this study, we examine the absorption lines of three of the eight GRBs with UV rest-frame spectra, namely, GRB 990123 (z = 1.601; Kulkarni et al. 1999), GRB 010222 (z = 1.475; Masetti et al. 2001; Jha et al. 2001; Salamanca et al. 2001; Mirabal et al. 2002), and GRB 000926 (z = 2.0379; Castro et al. 2003). We exclude GRB 970508 (z = 0.835; Metzger et al. 1997), GRB 990510 (z = 1.619; Vreeswijk et al. 2001), GRB 990712 (z = 0.4331; Vreeswijk et al. 2001), and GRB 011211 (Holland et al. 2002) for poor quality of the spectra and therefore lack of interesting absorption features.

2. GRB-DLA COLUMN DENSITY DETERMINATION

Similarly to QSO-DLAs, GRB-DLAs show strong Fe ii, Mg ii, and Si ii absorptions, together with relatively weak Zn ii and Cr ii. Table 1 lists oscillator strengths f0 (from the recent compilation by Prochaska et al. 2001) and rest-frame equivalent widths \( W' \) of absorption lines in the three GRBs used in the present analysis. The large \( W' \) of all these species relative to higher ionization species such as C iv, Si iii, and Si iv indicate that the medium is weakly ionized. From the equivalent widths (EWs), we derive column densities and directly compare the results with typical column densities in QSO-DLAs. Comparing column densities instead of metallicities [X/H] has the advantage that the H i column density (known only in GRB 000926 with large uncertainty; Fynbo et al. 2002) is not required. Moreover, it is not necessary to make any assumptions about the dust depletion, cosmic abundance, or ionization level of the considered element, but we can still search for similarities and differences between GRB-DLA and QSO-DLA.

A direct comparison is complicated by the fact that normally QSO-DLAs are observed at high spectral resolution (FWHM \( \approx 10 \) km s\(^{-1}\)) in a large wavelength range (thanks to echelle spectroscopy), allowing a good determination of

<table>
<thead>
<tr>
<th>LINE</th>
<th>( f_0 )</th>
<th>( W' ) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn ii λ2026</td>
<td>0.489</td>
<td>0.800 ± 0.065</td>
</tr>
<tr>
<td>Zn ii λ2062</td>
<td>0.256</td>
<td>0.800 ± 0.065</td>
</tr>
<tr>
<td>Si ii λ1526</td>
<td>0.127</td>
<td>2.64 ± 0.18</td>
</tr>
<tr>
<td>Si ii λ1808</td>
<td>0.00218</td>
<td>1.130 ± 0.089</td>
</tr>
<tr>
<td>Cr ii λ2056</td>
<td>0.105</td>
<td>0.650 ± 0.050</td>
</tr>
<tr>
<td>Cr ii λ2066</td>
<td>0.0151</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Cr ii λ2062</td>
<td>0.078</td>
<td>&lt;0.28 ± 0.14</td>
</tr>
<tr>
<td>Fe ii λ2344</td>
<td>0.00244</td>
<td>8.31 ± 0.11</td>
</tr>
<tr>
<td>Fe ii λ2374</td>
<td>0.0313</td>
<td>3.41 ± 0.24</td>
</tr>
<tr>
<td>Fe ii λ2382</td>
<td>0.320</td>
<td>3.07 ± 0.13</td>
</tr>
<tr>
<td>Fe ii λ2386</td>
<td>0.6691</td>
<td>1.09 ± 0.14</td>
</tr>
<tr>
<td>Fe ii λ600</td>
<td>0.239</td>
<td>3.65 ± 0.26</td>
</tr>
<tr>
<td>Mn ii λ2357</td>
<td>0.3508</td>
<td>...</td>
</tr>
<tr>
<td>Mn ii λ2359</td>
<td>0.2710</td>
<td>...</td>
</tr>
<tr>
<td>Mn ii λ2366</td>
<td>0.1927</td>
<td>...</td>
</tr>
</tbody>
</table>

\( ^b \) Lower error found assuming possible contamination from Mg i λ2066 line.
\( ^c \) Cr ii λ2062 contribution to the Zn ii λ2026 + Cr ii λ2062 blend is negligible.
\( ^d \) Noisy region of the spectrum, given only upper limit based on the total EW + 3σ, reported by Castro et al. 2003.
\( ^e \) Contribution of the Cr ii λ2062 line to the Zn ii λ2026 + Cr ii λ2062 blend calculated using the Cr ii column density as derived from Cr ii λ2056, 2066.
\( ^g \) Weighted from Salamanca et al. 2001 and Mirabal et al. 2002.
column densities of many ions, even in cases where saturated or weak lines in complex features are detected (see, e.g., Lu et al. 1996; Pettini et al. 1997; Prochaska & Wolfe 1999). On the other hand, the typical resolution of GRB optical spectra is FWHM > 100 km s^{-1}. Moreover, the majority of absorption lines are saturated, and it is not possible to use the linear part of the COG to determine column densities. However, the lines are numerous, so even if the uncertainty may be large, it is possible to make an abundance analysis using the general COG analysis (Spitzer 1978). Since the typical resolution of GRB spectra does not allow the separation of the different components of a complex feature, because of the many clouds along the line of sight, in our analysis we adopt a large "effective" Doppler parameter, being the result of the superposition of many narrow absorption lines. For reference, we note that typical velocities in QSO-DLAs are ~100 km s^{-1} or more. The COG analysis applied with the single-component approximation was used for QSO-ELA studies before high-resolution spectroscopy of QSOs became possible (see, e.g., Blades et al. 1982; Turnshek et al. 1989). In fact, Jenkins (1986) showed that the COG technique applied to complex features gives nearly the correct answer (the simulated-to-true column density ratio rarely goes below 0.8) even if different lines have very different saturation levels or Doppler parameters. This general result is also confirmed by Savage & Sembach (1991).

The best-fitting column density is determined by using simultaneously different EWs of various ions and choosing the COG with an effective Doppler parameter that minimizes the $\chi^2$. Once the best effective Doppler parameter is determined, the error on the column density for each ion is determined by varying $\log N$ for which $\chi^2/dof \leq 1$. In the following §§ 2.1–2.3, we discuss column density measurements in each individual GRB. Figures 1, 2, and 3 show the best-fitting $\langle W_p/\lambda \rangle$ and column densities and the corresponding COG. Estimated column densities are given in Table 2.

### 2.1. GRB 990123

The optical transient of GRB 990123 at $z = 1.6004$ was observed with the Keck/Low Resolution Imaging Spectrograph (LRIS; Kulkarni et al. 1999) for a final resolution and signal-to-noise ratio (S/N) of FWHM = 11.6 Å (400–700 km s^{-1}) and S/N ~ 30, respectively. The very weak Fe ii...
The optical transient of GRB 010222 at $z = 1.475$ was observed with the Fred Lawrence Whipple Observatory 1.5 m telescope (Jha et al. 2001; FWHM = 6 Å or 300–450 km s$^{-1}$, S/N $\approx 10$), with the 3.58 m Telescopio Nazionale Galileo (Maselli et al. 2001; FWHM = 4.8 Å or 200–400 km s$^{-1}$, S/N $\approx 10$), with the 4.2 m William Herschel Telescope (Salamanca et al. 2001; FWHM = 3.3–5.8 Å or $\sim 300$ km s$^{-1}$, S/N $\approx 10$), and with Keck/LRIS and ESI (Mirabal et al. 2002; FWHM = 11–13 Å or $\sim 650$ km s$^{-1}$, and FWHM = 0.4–0.8 Å or $\sim 30$ km s$^{-1}$). Even though the different spectra span a time interval of $\sim 27$ hr, starting 5 hr after the burst, the absorption-line EWs do not show significant time variability (Mirabal et al. 2002). Therefore, to obtain a better estimate of column densities, we combined the EWs of the same lines from different observations weighted according to the errors. We constrain the effective Doppler parameter to $b = 70$ km s$^{-1}$, using the Si II $\lambda 1526$ and Si II $\lambda 1808$ lines and seven Fe II lines (Fig. 3). We get log $N$(Si II) = 16.09 $\pm$ 0.05 and log $N$(Fe II) = 15.32$^{+0.05}_{-0.16}$. The Fe II lines are scattered in the COM diagram, probably because of nonuniform EW measurements by the four groups.

The Zn II $\lambda 2026$ line at $\lambda \approx 5018$ Å is blended with the Mg I $\lambda 2026$ line. The contamination of Mg I to this doublet is estimated using the Mg I $\lambda 2852$ line at $\lambda \approx 7065$ Å and $W_r$(Mg I $\lambda 2852$) = 1.22 $\pm$ 0.04 Å. Assuming an effective Doppler parameter $b > 35$ km s$^{-1}$, we get log $N$(Mg I) $< 14$ and $W_r$(Mg I $\lambda 2026$) $< 0.04$ Å. We then assume that the feature at $\lambda \approx 5018$ Å is dominated by the Zn II $\lambda 2026$ absorption, with $W_r = 0.79^{+0.05}_{-0.07}$ Å and the lower error determined by a possible contamination from Mg I $\lambda 2026$. The Cr II $\lambda 2056$ EW is very low; therefore, it must be weak or not at all saturated. From the Cr II $\lambda 2056$ and Cr II $\lambda 2066$ lines, we get log $N$(Cr II) = 14.04$^{+0.04}_{-0.04}$. From this, we calculate a contribution of Cr II to the Zn II $\lambda 2063$ + Cr II $\lambda 2062$ doublet of $W_r$(Cr II $\lambda 2062$) = 0.32$^{+0.04}_{-0.04}$ Å. For this doublet we use only the measurements given by Jha et al., Salamanca et al., and Mirabal et al. (weighted mean $W_r = 0.73 \pm 0.02$ Å) because the spectrum by Maselli et al. shows strong blending with other absorption lines. Once the Cr II contribution is taken into account, we derived $W_r$(Zn II $\lambda 2062$) = 0.41 $\pm$ 0.05 Å. Using also the Zn II $\lambda 2026$ detection, we obtain log $N$(Zn II) = 13.78 $\pm$ 0.07 for $b = 70$ km s$^{-1}$. The Mn II column density is obtained from the Mn II $\lambda 2576$, 2594, 2606 triplet. For $b = 70$ km s$^{-1}$, we get log $N$(Mn II) = 13.61$^{+0.08}_{-0.08}$.

3. HEAVY-ELEMENT ABUNDANCES IN GRB-DLAs

Figure 4 displays the QSO-DLA column density histograms of Fe II, Cr II, Zn II, and Si II. These column densities

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1. We have not used Al I measurements detected in GRB 000926 and GRB 010222 because not included in the QSO-DLA sample and because [Fe/Al] = $-0.3$ $\pm$ 0.3 and $-0.4$ $\pm$ 0.2 for GRB 000926 and GRB 010222, respectively, which is not particularly interesting for our discussion.