Gamma-ray burst afterglows and the nature of their host galaxies.

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4 VLT spectroscopy of GRB 990510 and GRB 990712; probing the faint and bright end of the GRB host galaxy population


Abstract. We present time-resolved optical spectroscopy of the afterglows of the gamma-ray bursts GRB 990510 and GRB 990712. Through the identification of several absorption lines in the first epoch GRB 990510 spectrum, we determine the redshift for this burst at $z \geq 1.619$. No clear emission lines are detected. The strength of the Mg i feature is indicative of a dense environment, most likely the host galaxy of GRB 990510. Although the host is extremely faint ($V > 28$), the GRB afterglow allows us to probe its interstellar medium and – in principle – to measure its metallicity. The optical spectrum of GRB 990712 (whose host galaxy is the brightest of the known GRB hosts at cosmological redshifts), shows clear features both in emission and absorption, at a redshift of $z = 0.4331 \pm 0.0004$. On the basis of several line emission diagnostic diagrams, we conclude that the host galaxy of GRB 990712 is most likely an HII galaxy. We derive a unreddened [OIII] star formation rate of $2.7 \pm 0.8 \, M_\odot \, yr^{-1}$. Correcting for the measured extinction intrinsic to the host galaxy ($A_V = 3.4^{+2.4}_{-1.4}$), this value increases to $35^{+178}_{-28} \, M_\odot \, yr^{-1}$. The [OIII] equivalent width, compared to that of field galaxies at $z \leq 1$, also suggests that the host of GRB 990712 is vigorously forming stars. We employ the oxygen and Hβ emission-line intensities to estimate the global oxygen abundance for the host of GRB 990712: log(O/H) = $-3.7 \pm 0.4$, which is slightly below the lowest metallicity one finds in nearby spiral galaxies. For both GRBs we study the time evolution of the absorption lines, whose equivalent width might be expected to change with time if the
burst resides in a dense compact medium. We find no evidence for a significant change in the MgII width.

### 4.1 Introduction

In February 1997, the Italian-Dutch satellite *BeppoSAX* enabled a breakthrough in the understanding of gamma-ray bursts (GRBs) by providing an accurate position for the prompt X-ray emission of a GRB. This led to the discovery of the first X-ray afterglow of a GRB (Costa et al. 1997), and, independently, to the identification of the first optical counterpart of a burster (Van Paradijs et al. 1997). Since then, several X-ray, optical and radio counterparts of GRBs have been detected. These multi-wavelength afterglow observations can be explained reasonably well by simple fireball models (for recent reviews see Piran 1999; Van Paradijs et al. 2000). GRB distance determinations are crucial in the effort to establish the physical nature of their progenitor(s). The observed redshift distribution of the ‘normal’ afterglows (i.e., excluding GRB 980425, which is associated with supernova SN1998bw at $z = 0.0085$ Galama et al. 1998b), ranges from $z = 0.43$ (Galama et al. 1999b, and this chapter) to $z = 3.42$ (Kulkarni et al. 1998b).

Although major advances in the understanding of GRBs have been made over the past few years (thanks to the detection of afterglows), the physical nature of their progenitor(s) remains unclear. The most popular models are (i) the collapse of a rotating massive star (Woosley 1993; MacFadyen & Woosley 1999) and (ii) the merging of two neutron stars, or a neutron star and a black hole (Narayan et al. 1992; Janka et al. 1999). The former (‘collapsar’) model has trouble producing GRBs with durations shorter than a couple of seconds and predicts that every afterglow is accompanied by a supernova of a type (Ic) similar to SN1998bw (MacFadyen & Woosley 1999). Furthermore, in the collapsar environment it is likely that the optical light of the afterglow is heavily absorbed by the surrounding dusty medium. Given the massive progenitors, one expects the frequency of GRBs to be strongly correlated with the cosmic star formation rate; the latter remains one of the great unresolved issues in astronomy of today. The compact star merger scenario can make short GRBs as well as long ones (although a $10^{15}$ G magnetic field is probably needed for the latter, see Mészáros 1998); some of these mergers are expected to occur in low-density environments, possibly located several kiloparsec outside their host galaxies. This is due to the large kick velocities imparted to the compact objects from the two respective supernovae (~ 250–300 km s$^{-1}$; Hansen & Phinney 1997), combined with the long time between the birth of the system and the merger occurrence (10$^{7}$–10$^{8}$ years; Portegies Zwart & Yungelson 1998). Consequently, since the optical afterglow brightness depends on the density of the circumsource medium, some of these bursts may not show an afterglow at all. These could account for the ‘dark’
burst population, i.e. bursts for which only X-ray afterglows have been found. One way to discriminate between these two models is by studying the immediate environment of the burst. In the collapsar model the circumsource density is expected to drop with distance as \( r^{-2} \), due to the expanding stellar wind of the SN progenitor, while in the binary merger scenario a constant, relatively low-density ambient medium is most plausible.

If the GRB source resides in a compact, gas-rich environment (which is expected in the collapsar scenario), the afterglow spectrum might show time-dependent absorption features (such as Ly\( \alpha \) and Mg\( \text{II} \)) due to the gradual ionization of the surrounding medium (Perna & Loeb 1998). In this case a decrease of the absorption-line equivalent widths (EWs) with time is expected. On the other hand, spectroscopic observations of the star HD 72089, situated behind the Vela supernova remnant, show an increase of an order of magnitude of the absorption strengths of elements such as Al and Fe, over the velocity range spanned by absorption in the remnant (Jenkins & Wallerstein 1995; Savage & Sembach 1996). This is attributed to the destruction of the dust grains, due to the propagation of the SN shock, which causes the release of elements (such as Fe and Mg) that are frozen in the dust. Thus in a dusty environment that is being ‘shocked’ by a GRB explosion, one might expect the strength of the absorption lines to increase in time.

In order to test these theories of GRB genesis, and the effects of GRBs on their environments, we have an on-going program to obtain spectra of GRB afterglows using the Very Large Telescope (VLT) of the European Southern Observatory (ESO) at Paranal, Chile. Here we present results on two of these bursts: GRB990510 and GRB990712.

### 4.1.1 GRB 990510

GRB990510 was observed on 1999 May 10.36743 UT with the Wide Field Camera (WFC) unit 2 onboard BeppoSAX, which localized the burst at R.A. = 13\(^{h}\)38\(^{m}\)06\(^{s}\), Decl. = -80\(^{\circ}\)29\('\)30" (J2000.0), with an error radius of 3' (Dadina et al. 1999). The BeppoSAX Gamma Ray Burst Monitor (GRBM) recorded an 80s event with a multi-peak structure (40–700 keV). The average and peak intensity in the WFC unit 2 (2–28 keV) was about 0.7 and 4.3 Crab, respectively. The burst position as determined with BeppoSAX is consistent with that of the Interplanetary Network (IPN; Hurley & Barthelmy 1999), using the Burst And Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory, and Ulysses. BATSE recorded a fluence above 20 keV of \( 2.56 \times 10^{-5} \) erg cm\(^{-2} \) (Kippen 1999), ranking it in the top 9% of the burst fluence distribution.

We discovered the optical afterglow on images taken at the South African Astronomical Observatory (SAAO) 1m telescope (Vreeswijk et al. 1999) and subsequently triggered our VLT program to take spectra and polarimetric images. Here, we present the time-
resolved spectroscopy. Our polarimetric observations resulted in the first polarization detection of a GRB afterglow (Wijers et al. 1999; Covino et al. 1999), while our photometric observations show an achromatic break in the BVRIJHK light curves, which is most likely due to the burst emission being collimated (Rol et al., in prep., see also Stanek et al. 1999; Harrison et al. 1999). Fruchter et al. (1999a) have used the Hubble Space Telescope (HST) to estimate $V_{\text{host}} > 28$, and do not find evidence for a supernova (SN) of the same type and brightness as SN 1998bw in the late-time light curve of GRB990510. Recent HST observations (April 2000) appear to detect a faint galaxy ($V \sim 28$) at the position of the early optical transient, which, if real, is most likely the host of GRB990510 (Fruchter et al. 2000a; Bloom 2000).

### 4.1.2 GRB 990712

GRB990712 triggered the GRBM and WFC unit 2 onboard BeppoSAX on 1999 July 12.69655 UT. The burst lasted for about 30s, had a double-peaked structure, was moderate in $\gamma$ rays, and was accompanied by one of the strongest prompt X-ray counterparts ever observed (Heise et al. 1999). The WFC unit 2 located the burst at R.A. = 22$^{h}$31$^{m}$50$^{s}$, Decl. = -73$^\circ$24'24" (J2000.0), with an error radius of $2\arcmin$. Unfortunately, neither flux nor fluence levels are reported in the literature. Again the SAAO 1m telescope was successful in hunting down the GRB afterglow (Bakos et al. 1999), which allowed us to quickly alert the VLT staff for spectroscopic, polarimetric and further photometric follow-up observations. The host galaxy of GRB990712 is the brightest of the known GRB host galaxies, with $R = 21.8$ and $V = 22.3$ (Sahu et al. 2000). The VLT polarimetric images exhibit a significant degree of polarization of the afterglow of GRB990712 which seems to vary with time, while the polarization angle does not change with time (Rol et al. 2000). These observations cannot be easily reconciled with afterglow polarization theories. The photometric measurements show a common temporal power-law decay of the transient source, overtaken by the bright host galaxy at late times; no evidence is found for a supernova of type SN1998bw (Sahu et al. 2000; Hjorth et al. 2000a,b).

The organization of this chapter is as follows: in §4.2 we present the observations and data reduction methods. In §4.3 we display and discuss the spectra of GRB990510, followed by GRB990712 in §4.4. We study the absorption-line intensity evolution in time for both bursts in §4.5 and describe our conclusions in §4.6.

### 4.2 Observations

After the optical identification of both GRB990510 (Vreeswijk et al. 1999) and GRB990712 (Bakos et al. 1999), we triggered our VLT target-of-opportunity observation program...
4.2 Observations

Table 4.1: Log of the GRB990510 and GRB990712 spectroscopic observations. The total exposure time for all spectra was 1800 sec.

<table>
<thead>
<tr>
<th>UT date (1999)</th>
<th>time since burst (days)</th>
<th>grism</th>
<th>wavelength range (Å)</th>
<th>resolving power</th>
<th>S/N at 6500 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB990510</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 11.179</td>
<td>0.811</td>
<td>G150I</td>
<td>3700–7700</td>
<td>185</td>
<td>91</td>
</tr>
<tr>
<td>May 11.203</td>
<td>0.836</td>
<td>G150I+OG590</td>
<td>6000–9000</td>
<td>280</td>
<td>78</td>
</tr>
<tr>
<td>May 12.123</td>
<td>1.755</td>
<td>G150I</td>
<td>3700–7700</td>
<td>185</td>
<td>6</td>
</tr>
<tr>
<td>May 12.146</td>
<td>1.779</td>
<td>G150I+OG590</td>
<td>6000–9000</td>
<td>280</td>
<td>6</td>
</tr>
<tr>
<td>May 14.237</td>
<td>3.906</td>
<td>G300V &amp; G300I</td>
<td>3880–9255</td>
<td>420 &amp; 680</td>
<td>9</td>
</tr>
<tr>
<td>May 16.254</td>
<td>5.887</td>
<td>G150I</td>
<td>3700–7700</td>
<td>185</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB990712</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 13.182</td>
<td>0.485</td>
<td>G150I</td>
<td>3700–7700</td>
<td>185</td>
<td>26</td>
</tr>
<tr>
<td>July 13.421</td>
<td>0.725</td>
<td>G150I</td>
<td>3700–7700</td>
<td>185</td>
<td>21</td>
</tr>
<tr>
<td>July 14.181</td>
<td>1.485</td>
<td>G150I</td>
<td>3700–7700</td>
<td>185</td>
<td>14</td>
</tr>
</tbody>
</table>

and obtained several low-resolution spectra at various epochs with the {\em FOcal Reducer and low-dispersion Spectrograph} (FORS), mounted at the Cassegrain focus of the ESO VLT-UT1 Antu telescope. The date of observation, grism used, wavelength range, resolving power and the signal-to-noise at 6500 Å are listed in Table 4.1. A slit width of 1" was used for all spectra. Grism G150I approximately covers the wavelength range 3700–9000 Å. However, redward of 6500 Å the second order starts to contaminate the first order (cf. FORS User Manual 1.3). To obtain a clean spectrum longward of 6500 Å for GRB990510, we also took spectra with an order separation filter (OG590), using the same grism. However, due to the low sensitivity of the CCD shortward of 3700 Å, the impact of the overlap is negligible shortward of 7700 Å. Therefore, we have summed the blue and red spectra over the region 6200–7700 Å and combined this part with the single blue and red spectra into a continuous spectrum over the entire wavelength range. For the grisms G300V and G300I, we have simply connected the blue and red parts into one spectrum. For GRB990712, we used grism G150I without order separation filter, and thus these spectra are usable over the wavelength range 3700–7700 Å.

The raw spectra were bias-subtracted, and flat-fielded with a normalized combined set of lamp flat-fields. Subsequently, cosmic rays were removed interactively along the afterglow spectrum and each sequence of images was summed into combined images. The spectra were optimally extracted from the combined images, and wavelength calibrated using a standard Helium-Neon-Argon lamp. The r.m.s. error in the wavelength calibration is approximately 0.25 Å. Since no useful spectra of standard stars were taken neither during the first two nights for GRB990510 nor for GRB990712, we have flux-
calibrated these spectra using the BVRI light curve data of Rol et al. (in prep.) for GRB 990510 and the VRI data of Sahu et al. (2000) for GRB 990712. The spectra of the other nights were flux-calibrated with a spectrophotometric standard star, which resulted in flux levels that are consistent with the photometry at the same epochs.

To flux-calibrate the spectrum of GRB 990510, we fitted the light curves with a smoothly connected broken-power-law model (Harrison et al. 1999; Stanek et al. 1999; Beuermann et al. 1999), while for GRB 990712 we used a simple power-law model with a host galaxy contribution. We determined the magnitudes at the times when the spectra were taken (see Table 4.1), using the fits to the light curves. These values were then corrected for the estimated Galactic foreground extinction: E(B−V) = 0.2 and E(B−V) = 0.03 (Schlegel et al. 1998) for the May and July burst, respectively. The E(B−V) value is translated into an extinction at a given wavelength using the standard Galactic extinction curve of Cardelli et al. (1989). The magnitudes were transformed to fluxes (Fukugita et al. 1995) and were fitted with a power-law spectrum F ∝ ν^β. For GRB 990510 we find β = −0.6 ± 0.1 (first night), and β = −0.7 ± 0.1 (second night). For the three spectra of GRB 990712 we obtain β(1) = −1.1 ± 0.2, β(2) = −0.9 ± 0.2 and β(3) = −0.9 ± 0.2. We have not taken into account the extinction intrinsic to the host galaxy; see §4.4. These slopes are quite usual for GRB afterglows. We also fitted the global profile (excluding the absorption and emission lines) of all the wavelength-calibrated spectra with a 4th-order Chebychev polynomial. To obtain the flux-calibrated spectra, we multiplied the wavelength-calibrated spectra by the ratio between the power-law fit based on the photometry and the global spectral profile fit. We estimate the error in the flux calibration for all nights to be about 15%.

The equivalent width (EW) of the spectral lines was measured using the splot routine in IRAF; we used both a Gaussian fit, and also simply summed the difference between the pixel value and the continuum for each pixel over the line. Both methods gave similar results. The error is mostly dominated by the uncertainty in the continuum level, which was estimated by placing the continuum at a high and low level (roughly corresponding to the ± r.m.s. value of the continuum in the vicinity of the line). We take the mean value of these two estimates as the EW, and half their difference as the error. We also calculate the Poisson error from the object and sky spectrum, which we quadratically sum with the measurement error to obtain the total error. We then corrected the EW for the host galaxy contribution in case of absorption features (i.e. divided the measured EW by the afterglow fraction of the total light) and for the afterglow contribution in case of an emission line (i.e. divided by the galaxy-light fraction of the total). The host galaxy fraction of the total light for GRB 990510 is negligible (see §4.3), while for GRB 990712 we obtain 0.23 ± 0.03, 0.30 ± 0.04 and 0.47 ± 0.06 for epoch one, two and three, respectively, from the V and R band light curve fits of Sahu et al. (2000). The error was estimated from the different values for the host galaxy magnitude as given by Sahu et al. (2000) and Hjorth et al. (2000b). These errors are propagated along with
4.3 The absorption-line spectrum of GRB 990510

Table 4.2: Absorption lines in GRB 990510. $W_\lambda$ is given in the absorber's rest frame, i.e. the observed value is divided by $(1+z)$. The error in $W_\lambda$ is dominated by the uncertainty in the placing of the continuum. The relative error expected from Poisson statistics and read noise is given in parentheses. The weighted mean redshift is calculated, using the separate measurements of all the lines, even though the identification of AlIII and CrII/ZnII is uncertain (see text).

<table>
<thead>
<tr>
<th>$\lambda_{\text{obs}}$ (Å)</th>
<th>ID</th>
<th>$z_{\text{abs}}$</th>
<th>$W_{\lambda_{\text{rest}}}$(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4883 ± 6</td>
<td>AlIII(1862.79)?</td>
<td>1.6213 ± 0.0032</td>
<td>0.8 ± 0.6 (0.010)</td>
</tr>
<tr>
<td>5396 ± 5</td>
<td>CrII(2062.23)/ZnII(2062.66)?</td>
<td>1.6166 ± 0.0024</td>
<td>0.8 ± 0.3 (0.010)</td>
</tr>
<tr>
<td>6142 ± 3</td>
<td>FeII(2344.21)</td>
<td>1.6201 ± 0.0013</td>
<td>0.6 ± 0.2 (0.011)</td>
</tr>
<tr>
<td>6241 ± 5</td>
<td>FeII(2382.76)</td>
<td>1.6192 ± 0.0021</td>
<td>0.5 ± 0.3 (0.012)</td>
</tr>
<tr>
<td>6806 ± 3</td>
<td>FeII(2600.17)</td>
<td>1.6175 ± 0.0011</td>
<td>0.9 ± 0.2 (0.011)</td>
</tr>
<tr>
<td>7335 ± 2</td>
<td>MgII(2796.35/2803.53)</td>
<td>1.6197 ± 0.0034</td>
<td>2.6 ± 0.4 (0.017)</td>
</tr>
<tr>
<td>7472 ± 6</td>
<td>MgI(2852.96)</td>
<td>1.6190 ± 0.0021</td>
<td>0.6 ± 0.2 (0.013)</td>
</tr>
<tr>
<td></td>
<td>weighted mean:</td>
<td>1.6187 ± 0.0015</td>
<td></td>
</tr>
</tbody>
</table>

the errors in the EW measurements. Finally the EW is converted to the rest frame by dividing by $(1+z)$. The emission-line fluxes are independent of the afterglow contribution to the total light.

We have identified several absorption lines in the first epoch spectrum of GRB 990510: MgII λ2800, MgI λ2853, FeII λ2344,2383,2600, and possibly AlIII λ1863 and CrII/ZnII λ2062. The observed wavelengths, identifications, corresponding redshifts, and equivalent widths (in the absorber's rest frame) are listed in Table 4.2. The lines and the telluric absorption features are also indicated in Fig. 4.1.

4.3 The absorption-line spectrum of GRB 990510

These line identifications can be verified by taking into account the oscillator strength, ionization potential and relative cosmic abundance. The observed EWs of FeII at 2344 Å, 2383 Å, and 2600 Å are in reasonable agreement with their relative oscillator strengths (Morton 1991). Other FeII lines, such as FeII λ1608 and FeII λ2587 were not observed, but these have smaller oscillator strengths, consistent with their non-detection. However, the oscillator strength of the undetected AlIII λ1855 is twice that of the detected AlIII λ1863 line, and so should have been detected at an observed wavelength of 4858 Å. This makes the identification of the line at 4883 Å with AlIII questionable. A similar argument can be made for the reality of the CrII/ZnII λ2062 line. Both lines are expected to be accompanied by a stronger partner (CrII λ2056 and ZnII λ2026), which is not detected.
Figure 4.1: VLT/FORS1 spectra of the afterglow of GRB990510; 0.8 and 3.9 days after the burst. The error spectra, calculated from the object and sky spectra using Poisson statistics, are also shown. Several absorption features (including telluric lines marked with ©) are indicated with the broken lines.

The presence of FeII suggests that the medium probed with our line of sight is most likely one of low-ionization, and therefore HII λ1670 is expected to be present as well given the similarity between the Fe and Al ionization potentials, but again nothing is detected. However, we clearly detect MgII, which is a blend of MgII λ2796 and MgII λ2804, and observe MgI λ2853 in absorption as well.

The weighted mean redshift of the identified lines is $z = 1.6187 \pm 0.0015$. On the basis of this redshift we can possibly identify FeII(2250) at 5893 Å, although we do not expect to detect this line due to its low oscillator strength. Since no clear emission lines are detected, this redshift is certainly a lower limit to the redshift of the GRB afterglow. However, the strength of MgI λ2853 suggests we are probing a dense, low-ionization medium, very likely that of the host galaxy. Assuming isotropic emission, $z = 1.619$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0=0.3$, and $\Lambda=0$, we find a luminosity distance of $3.5 \times 10^{28}$ cm, corresponding to an ($> 20$ keV) energy output of $1.5 \times 10^{53}$ erg for GRB990510, based
4.3 The absorption-line spectrum of GRB 990510

on the BATSE fluence of $2.56 \times 10^{-5}$ erg cm$^{-2}$ (Kippen 1999; Briggs et al. 2000).

Unfortunately, the spectra taken on May 12 and May 16 (not shown in Fig. 4.1) are of inferior quality, and cannot be used for absorption-line measurements. In the May 14 spectrum, however, we detect Mg II again. The observed wavelength of $\lambda_{\text{obs}} = 7327 \pm 5$ Å is consistent with the redshift determined in the first epoch spectrum. Its equivalent width is $W_{\text{rest}} = 2.3 \pm 0.6$ Å, which is (within the errors) identical to the measurement of May 11.2 1999 UT (0.8 days after the burst; $W_{\text{rest}} = 2.6 \pm 0.4$ Å). For the other absorption lines detected earlier it is not possible to obtain an accurate measurement of their EW.

We will now derive a lower limit to the H I column in the direction of GRB 990510 from the Fe II lines at 2344 Å, 2600 Å, and 2383 Å in the first epoch spectrum. The relation between the EW of a line, $W_\lambda$, its column density, $N_j$ (number of atoms in the corresponding ionization state), and the oscillator strength, $f$, of the transition (j) is (Spitzer 1978):

$$\log W_\lambda = \log (N_j \times \lambda \times f) - 4.053$$

Here the unit of $W_\lambda$ is Å, the column density $N_j$ is in cm$^{-2}$ and the wavelength $\lambda$ is in cm. We do not use the strongest absorption line, Mg II $\lambda$2800, since this line is easily saturated in typical galaxy spectra, placing it on the flat part of the curve of growth ($W_\lambda$ versus $N_j \times \lambda \times f$). Even if the error in the EW determination were very small, this would still lead to a very uncertain value for the column density. The Mg II line is not used either, due to the large uncertainty in the ratio of Mg II to Mg I, translating in a similar uncertainty in the column density. Fe II, however, should be the dominant Fe ion in a dense neutral environment. The following holds if the Fe lines are not saturated. Using the oscillator strength values from Morton (1991) for these lines ($f($Fe II $\lambda$2344$)=0.110$, $f($Fe II $\lambda$2383$)=0.301$ and $f($Fe II $\lambda$2600$)=0.224$), and the values for $W_\lambda$ obtained from the spectrum of the first epoch (see Table 4.2), we obtain $\log N($Fe II $\lambda$2344$) = 14.0 \pm 0.1$ cm$^{-2}$, $\log N($Fe II $\lambda$2383$) = 13.5 \pm 0.2$ cm$^{-2}$ and $\log N($Fe II $\lambda$2600$) = 13.8 \pm 0.1$ cm$^{-2}$.

We adopt the value $\log N(\text{Fe}) = 13.8 \pm 0.2$ cm$^{-2}$. Even though the EWs of the three different Fe lines result in similar values for the column, the lines are probably saturated, i.e. our estimate for the Fe column density should be considered as a lower limit.

In converting the number of Fe atoms to a hydrogen column density, we have to take into account that the metallicity in high-redshift galaxies is likely to be lower than the Galactic value, and that a large fraction of the Fe atoms can be hidden in dust (Whittet 1992). A study of the metallicity in damped Ly$\alpha$ systems (which have $N(\text{H I}) \gtrsim 10^{20}$cm$^{-2}$) from $z = 0.7$ to 3.4 (Pettini et al. 1997) (we adopt $[\text{Zn/H}] = -0.8$), allows us to estimate the Fe abundance at the redshift of GRB 990510 with respect to the solar abundance (log(Fe/H)$_{\odot} = -4.5$; Grevesse & Sauval 1999), obtaining $\log(N(\text{Fe})/N(\text{H})) = -5.3$. The Galactic Fe depletion factor in a cool disk environment is $-2.2$ dex (Sem-
bach & Savage 1996; Savage & Sembach 1996), but here we adopt the typical depletion measured in damped Lyα systems, which is around $-0.6$ dex. Taking all these points into account gives the following rough lower limit to the hydrogen column density: $\log N(\text{HI}) \geq 19.7 \text{ cm}^{-2}$. Another and more robust way of estimating the HI column density which is independent of dust corrections, is to use the FeII measured in DLAs (the gas phase only) around the redshift of the GRB. Using 10 systems with redshifts ranging from 1.2 to 2.0, we find $\text{[Fe/H]} = -1.5 \pm 0.5$. Assuming that this is the most likely [Fe/H] abundance for the host galaxy of GRB 990510, we obtain $\log N(\text{HI}) \geq 13.8 + 1.5 + 4.5 \text{ cm}^{-2} = 19.8 \text{ cm}^{-2}$, very close to our first estimate. A low column density is consistent with that found by Briggs et al. (2000) from fitting a combined set of BATSE and BeppoSAX X-ray and γ-ray data.

HST imaging, performed in April 2000, appears to detect a very faint ($V \sim 28$) galaxy, located only 0.08″ East of the position of the early afterglow (Fruchter et al. 2000a; Bloom 2000). This galaxy is probably responsible for the detected absorption lines in the spectra. The type and strength of the absorption lines, which are indicative of a low-ionization, high-density medium, strongly suggest that these originate in the host galaxy of GRB 990510. Even though the galaxy is extremely faint, the GRB afterglow allows us to probe its interstellar medium and – in principle – to measure its metallicity. For the latter we need a measure of the column density that does not depend on the strength of the metal absorption lines (e.g. from a Balmer feature).

### 4.4 The emission- and absorption-line spectrum of GRB 990712

Fig. 4.2 shows the spectra of GRB 990712, taken at 0.5, 0.7 and 1.5 days after the burst (see Table 4.1). The obvious emission lines are easily identified as [OII] $\lambda 3727$, [NeIII] $\lambda 3869$, Hγ, Hδ, and [OIII] $\lambda\lambda 4959,5007$. We also detect two absorption lines, which can be identified as MgII $\lambda 2796,2804$ and MgI $\lambda 2853$ at the same redshift as the emission lines, and are therefore intrinsic to the host galaxy. Using all these features in all three spectra, we obtain a weighted average redshift of $z = 0.4331 \pm 0.0004$. In Table 4.3 we list the observed wavelength of the features, their identification and redshift, and the rest frame EW and flux (corrected for the Galactic foreground extinction), for the spectra taken at different epochs. The last two columns contain the EW and flux values averaged over all the spectra.

It is important to investigate whether GRB host galaxies are indeed star forming galaxies, i.e. HII galaxies, where massive O and B stars ionize the interstellar medium, giving rise to prominent emission lines. These lines are also observed in galaxies that host an active galactic nucleus (AGN, e.g. Seyfert 2), where their strength does not only depend on
Table 4.3: Absorption and emission lines in GRB 990712. All flux units are in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ and all line fluxes have been corrected for the Galactic foreground extinction.

<table>
<thead>
<tr>
<th>$\lambda_{	ext{obs}}$ (Å)</th>
<th>ID/Line</th>
<th>$z$</th>
<th>July 13.18</th>
<th>July 13.42</th>
<th>July 14.18</th>
<th>weighted mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$W_{\lambda,\text{rest}}$ (Å)</td>
<td>Line flux</td>
<td>$W_{\lambda,\text{rest}}$ (Å)</td>
<td>Line flux</td>
</tr>
<tr>
<td>4015 ± 6</td>
<td>Mg II λ2800</td>
<td>0.4330 ± 0.0004</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>4086 ± 6</td>
<td>Mg II λ2653</td>
<td>0.4373 ± 0.0019</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>5142 ± 3</td>
<td>[Ne III] λ3869</td>
<td>0.4332 ± 0.0003</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>5545 ± 4</td>
<td>[Ne III] λ3869</td>
<td>0.4332 ± 0.0003</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>6220 ± 3</td>
<td>Hα λ4340</td>
<td>0.4332 ± 0.0003</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>6966 ± 3</td>
<td>Hβ λ4861</td>
<td>0.4330 ± 0.0004</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>7106 ± 3</td>
<td>[O III] λ4959</td>
<td>0.4330 ± 0.0004</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
<tr>
<td>7175 ± 2</td>
<td>[O III] λ5007</td>
<td>0.4330 ± 0.0004</td>
<td>−114 ± 17</td>
<td>6.04 ± 0.31</td>
<td>−111 ± 15</td>
<td>6.15 ± 0.25</td>
</tr>
</tbody>
</table>

(mean: 0.4331 ± 0.0004)
Figure 4.2: VLT/FORS1 spectra of the afterglow of GRB 990712, from 0.5 to 1.5 days after the burst. The error spectra, calculated from the object and sky spectra using Poisson statistics, are also shown. The absorption features (including telluric lines marked with \( \oplus \)) and emission features are indicated with the broken lines. The observation dates (also shown in the figure), grisms, resolving power and signal-to-noise ratios are listed in Table 4.1.

the star formation, but on the nuclear activity as well. Most popular GRB progenitor models require a close connection with massive-star formation, but so far, this has not been confirmed for any of the host galaxies.
The emission- and absorption-line spectrum of GRB 990712

Hjorth et al. (2000b) suggested that the host galaxy of GRB 990712 may be a Seyfert 2 galaxy on the basis of the [OIII] $\lambda 5007/H\beta$ ratio being greater than three (see Shuder & Osterbrock 1981), and its location in the $\log([\text{OIII}] \lambda 5007/H\beta)$ vs. $\log([\text{OII}] /[\text{OIII}] \lambda 5007)$ diagram (see Fig. 2 of Baldwin et al. 1981). We also measure a ratio of [OIII] $\lambda 5007/H\beta$ that is greater than three: $4.6 \pm 1.0$. However, from the more recent work of Rola et al. (1997), who employ the Canada-France Redshift Survey (CFRS) sample of emission-line galaxies at redshifts $0 < z < 0.3$, it is clear that a value of 4.6 is actually very typical for HII galaxies (see their Fig. 1). Combined with our value for $\log([\text{OII}] / H\beta)$ of $0.4 \pm 0.1$, the host of GRB 990712 is located clearly within the HII galaxy regime. We note that this diagram is corrected for extinction intrinsic to the distant galaxies, while the values in our Table 4.3 are not. However, the [OIII] $\lambda 5007/H\beta$ ratio is only slightly affected by reddening. Rola et al. (1997) also build non-extinction corrected diagrams to distinguish between HII galaxies and other emission-line galaxies; in all but one of these, where its location is on the border of the HII galaxy and Seyfert 2 regimes, the host galaxy of GRB 990712 is classified as an HII galaxy (e.g. Table 4.3 gives $C_{3727} - C_{4861} = -0.28 \pm 0.03$, whereas Fig. 4 of Rola et al. (1997) shows all definite Seyfert 2s have $C_{3727} - C_{4861} > 0.4$), i.e. the emission lines are produced by HII regions that are being ionized by O and B stars. We conclude that GRB 990712 is most likely an HII galaxy, and not a Seyfert 2.

We have estimated the host galaxy extinction, by comparing the observed ratio of $H\gamma/H\beta$ ($0.26 \pm 0.09$) with the expected ratio for case B recombination ($0.469 \pm 0.009$; Osterbrock 1989). Using the Galactic extinction curve of Cardelli et al. (1989), we obtain $A_V = 3.4^{+4.4}_{-1.4}$. The relatively large error is due to the marginal detection of $H\gamma$.

We can now estimate the star formation rate (SFR) in the host galaxy of GRB 990712 in three different ways: through the [OIII] and H$\beta$ line luminosities (Kennicutt 1998), and through the continuum flux at 2800 Å (Madau et al. 1998). For all these estimates a Salpeter initial mass function (IMF) has been assumed. Combining Eq. 3 of Kennicutt (1998), a luminosity distance of $6.8 \times 10^{27}$ cm (taking $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0=0.3$, and $\Lambda=0$), and the [OIII] $\lambda 3727$ line flux from Table 4.3 (the fluxes in this table have already been corrected for Galactic extinction) we obtain SFR([OIII]) = $2.7 \pm 0.8$ M$_\odot$ yr$^{-1}$, consistent with the value found by Hjorth et al. (2000a). Taking into account the measured extinction (at H$\alpha$, due to the fact that the [OIII] SFR method is calibrated through H$\alpha$), using the Galactic extinction curve (Cardelli et al. 1989), we find SFR([OIII]) = $35^{+178}_{-25}$ M$_\odot$ yr$^{-1}$. Using Eq. 2 of Kennicutt (1998), the case B (large optical depth) line ratio $j_{H\alpha}/j_{H\beta}$ of 2.85 Osterbrock (1989) and the H$\beta$ flux of Table 4.3, we find SFR(H$\beta$) = $1.7 \pm 0.6$ M$_\odot$ yr$^{-1}$. Corrected for reddening, this becomes SFR(H$\beta$) = $64^{+770}_{-54}$ M$_\odot$ yr$^{-1}$. Finally, Eq. 2 of Madau et al. (1998), combined with the 2800 Å flux (which is located at 4013 Å at a redshift of 0.4331), gives SFR(2800 Å) = $2.8 \pm 0.9$ M$_\odot$ yr$^{-1}$, which becomes $\sim 400$ M$_\odot$ yr$^{-1}$, using $A_V = 3.4$. The [OIII] method, although it is indirectly calibrated through H$\alpha$ and sensitive to the abundance and ionization state of...
the gas, is probably the least uncertain of the three. The Hβ estimate is uncertain due to the unknown host galaxy stellar absorption underneath the emission. The SFR based on the ultra-violet continuum is very uncertain due to the fact that our flux calibration is an extrapolation below the V band, and, more importantly, the extinction correction at ultra-violet wavelengths is very uncertain. Normally, the 2800 Å SFR is found to be lower by a factor of 2–3 (at redshifts up to z = 2.8) as compared to the Hα luminosity SFR method (Glazebrook et al. 1999; Yan et al. 1999).

For the GRB host galaxies for which a SFR has been determined so far, even for the [OII] method alone, the values range from 0.5 ± 0.15 M⊙ yr⁻¹ (GRB 970228: Djorgovski et al. 1999b) to 20 ± 9 M⊙ yr⁻¹ (GRB 980703: Djorgovski et al. 1998); host galaxy extinction is not included, so these values should be considered as lower limits. Normalized by the host B band luminosity, this range is narrowed down to spread a factor of three. It has been noted (e.g. Djorgovski et al. 1998), that the range of SFRs for GRB host galaxies does not seem to be extra-ordinarily high, as compared to field galaxies at similar redshifts. E.g. Glazebrook et al. (1999) find a range of 20–60 M⊙ yr⁻¹ (using Hα), for 13 field galaxies at z = 1, drawn from the CFRS. However, the galaxies at high redshifts for which these rates have been measured tend to be much brighter than the typical GRB host galaxy, and are therefore expected to have much higher SFRs. The [OII] equivalent width, which effectively is the star formation rate normalized by the blue band luminosity of the host galaxy, allows a more useful comparison. The mean W_rst([OII]) of the Glazebrook et al. sample is 33 with a standard deviation of 15 Å, while we measure W_rst([OII]) = 46 ± 1 Å for the host of GRB990712. This comparison also suggests that GRB990712 occurred in a galaxy that is vigorously forming stars.

Using the oxygen and Hβ emission lines, we can estimate the global oxygen abundance of the host of GRB990712 (see Kobulnicky et al. 1999, and references therein). From the values in Table 4.3 we obtain \( R_{23} = (I_{3727} + I_{4959} + I_{5007})/H\beta = 8.9 \pm 1.5 \), corresponding to \( \log(O/H) = -3.7 \pm 0.4 \) (we note that \( \log(O/H)_{\odot} = -3.1 \); Cox 2000). This estimate is based on fluxes not corrected for reddening, but such a correction would not change the abundance estimate substantially. For comparison: the oxygen abundances for a sample of 22 relatively nearby spiral galaxies range from \( \log(O/H) = -2.7 \) to \( -3.5 \) (Kobulnicky et al. 1999).

### 4.5 The time dependence of the MgII feature

It is now well established that GRBs are the most energetic events in the universe, with peak isotropic luminosities up to \( 10^{53} \) erg s⁻¹ (Kulkarni et al. 1998b). Also when the radiation from GRBs is beamed, the impact of the shock on the circumburst material is the same as in an isotropic explosion, and could be observable as time-resolved evolution of the Fe Kα line and edge in the X-ray regime (Weth et al. 2000, and references therein)
and of ultra-violet (UV) absorption lines, redshifted to the optical domain (Perna & Loeb 1998). By monitoring the line evolution it is possible to obtain information on the density structure surrounding the explosion, and – in case the density can be measured by an independent method – the redshift to the burst may be obtained (Perna & Loeb 1998).

Our spectral observations of the afterglows of GRB 990510 and GRB 990712 extend over several nights, and both contain absorption lines, so that we can look for possible temporal evolution of these features. They are expected to decrease in time, if a considerable fraction of the atoms responsible for the absorption are in the vicinity of the site of the burst, and are ionized by the explosion (Perna & Loeb 1998). Alternatively, the burst may release atoms that are locked in the dust, which could result in a corresponding increase of the EWs. The clearest absorption feature in both bursts is Mg ii. In the May 11 and May 14 spectra of GRB 990510 (0.8 and 3.9 days after the burst, respectively), we measure $W_{\text{rest}} = 2.6 \pm 0.4$ Å (May 11) and $W_{\text{rest}} = 2.3 \pm 0.6$ Å (May 14). For GRB 990712 we obtain $W_{\text{rest}} = 8.3 \pm 1.4$ Å, $W_{\text{rest}} = 9.7 \pm 1.9$ Å and $W_{\text{rest}} = 13.7 \pm 4.5$ Å for 0.5, 0.7 and 1.5 days after the burst, respectively. For both bursts, the values are constant within the errors. This is not very surprising; the Mg ii feature is most likely saturated in the spectra of both bursts. This means that over a wide range of column densities, the EW is not expected to change by a detectable amount. On the other hand, a significant change in the EW would have indicated a large change in the column density. The Mg ii feature in GRB 990712, which is possibly saturated as well, is also constant within the errors.

### 4.6 Conclusions

GRB afterglows allow us to probe galaxies that would otherwise be extremely difficult or impossible to study spectroscopically. We have determined a lower limit to the redshift of GRB 990510 through identification of several spectral absorption lines. The strength of the Mg ii line is indicative of a cool, dense environment, which leads to the conclusion that the measured $z = 1.6187 \pm 0.0015$ most likely reflects absorption in the host galaxy ISM.

Using both the absorption and emission lines in the spectrum of GRB 990712, we determine its redshift at $z = 0.4331 \pm 0.0004$. The emission-line ratios indicate that the host of GRB 990712 is an H II galaxy, with an [OII] star formation rate (reddening corrected) of $35^{+178}_{-25}$ $M_\odot$ yr$^{-1}$. The large [OII] equivalent width, compared to that of field galaxies at $z \lesssim 1$, also suggests that the host is vigorously forming stars.

In order to put meaningful constraints on the circumsource medium, high resolution, high signal-to-noise spectra at several epochs after the burst are needed to resolve the...
velocity structures of the non-saturated lines, and allow determination of the circum-
source density distribution and its evolution. This may become possible with the launch
of HETE-II, since this satellite will allow follow-up observations of optical transients at
early times, i.e. when they are bright ($R \sim 16$). Determination of the density profile
could provide a major advance in solving the progenitor problem.

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Consortium guaranteed time.