Gamma-ray burst afterglows and the nature of their host galaxies.
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6 Afterglow spectroscopy and host
galaxy imaging of GRB 991216

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Abstract. We present a low-resolution spectrum of the optical afterglow of GRB 991216,
taken 1.5 days after the burst with the Very Large Telescope (VLT), and deep images
of the host galaxy, obtained 4 months later with the Hubble Space Telescope (HST).
The spectrum shows three possible absorption-line systems at $z = 0.77$, $z = 0.80$ and
$z = 1.02$, where the highest redshift most likely reflects the distance to the host galaxy.
The HST images are consistent with these findings: they show two amorphous regions of
emission, one at the projected OT position, the presumed host galaxy at $z = 1.02$, and
the other $0^\prime.6$ away, which is possibly responsible for the absorption lines at $z = 0.80$.
An alternative explanation is that both emitting regions are at $z = 1.02$ and part of the
same galaxy, or that they are in the process of merging. The $z = 0.77$ and $z = 0.80$
systems could originate in the halos of the two galaxies that are located roughly 2" away
from the transient.

6.1 Introduction

During the first five years of gamma-ray burst (GRB) afterglow studies (1997 through
2001), nearly 30 optical counterparts were discovered\(^1\) (e.g. Van Paradijs et al. 2000). Redshifts
have been securely determined for roughly two-thirds of these, with a median
value of around $z = 1$ (see Bloom et al. 2001b) and up to $z = 4.5$ (Andersen et al. 2000).
For just about all afterglows a host galaxy has been detected, ranging in magnitude

\(^1\)see http://www.aip.de/~jcg/grb.html for an overview of detected counterparts and references
from roughly $V = 22$ to $V = 30$ (A. Levan, private comm., see also Hogg & Fruchter 1999). These observations, i.e. the detection of afterglows (of the class of long-duration GRBs), their distance determination, and the inferred position of the early afterglow with respect to its host galaxy, have led to the general expectation that long bursts are produced by the collapse of massive stars, as proposed by Woosley and colleagues (Woosley 1993; MacFadyen & Woosley 1999).

The redshifts have been determined either through absorption-line spectroscopy of the bright early afterglow (e.g. Metzger et al. 1997), or through the detection of host-galaxy emission lines (e.g. Kulkarni et al. 1999). The latter have shown GRB host galaxies to be actively star-forming galaxies (e.g. Vreeswijk et al. 2001b). We note that in one case, for GRB 000131, the redshift was inferred from a sharp break around 6700 Å, interpreted as the Lyman break at $z = 4.5$ (Andersen et al. 2000). Since a considerable fraction of the hosts are very faint, detecting emission lines can be very time-consuming, if not unfeasible, with current instrumentation. Rapid spectroscopy is therefore needed to ascertain a redshift determination and, provided that the afterglow has been promptly identified, it does not require long integration times. Besides obtaining the redshift, rapid spectroscopy also provides the opportunity to study the host-galaxy density (e.g. Fynbo et al. 2001), kinematics (e.g. Castro et al. 2001a) and metallicity (e.g. Salamanca et al. 2002), provided that the spectrum has been taken with sufficiently high spectral resolution. Any foreground system that lies on the GRB line of sight can be studied with the same detail, just like metal absorption-line systems in QSO sight lines. One advantage over QSO absorption-line studies is that the GRB afterglow will fade away, which can allow a clean inspection of the intervening system in emission, while a background quasar generally hampers any faint detection.

In this chapter we present VLT spectroscopy of the afterglow and host galaxy imaging with HST of GRB 991216. The optical/infrared afterglow of GRB 991216 is one of a number of GRB afterglows (as e.g. GRB 990510; see Harrison et al. 1999; Pian et al. 2001) to show evidence for a “beaming” break (Rhoads 1997), suggesting that the gamma-ray, X-ray, and early optical emission was confined into jets (Halpern et al. 2000). Although the optical through X-ray data can be explained with a jet fireball model, inclusion of the radio data calls for more exotic models (Frail et al. 2000a, Rol et al. 2002, in prep.). This underlines the importance of observing GRB afterglows over a wide range in frequency. Chandra spectral observations of the X-ray afterglow show two probable emission features (Piro et al. 2000), that can be identified with an iron line and recombination continuum at a redshift of $z = 1.00 \pm 0.02$. These features suggest the presence of $0.01-1 \, M_\odot$ of iron in the vicinity of the burst (Piro et al. 2000; Vietri et al. 2001).

This chapter is organized as follows: in §6.2 we present VLT spectroscopy of the early afterglow, which allows us to establish the probable redshift of the burster. We find indications for two more systems along the line of sight. HST imaging of the host galaxy
shows two amorphous regions of light with a total magnitude of \( R = 24.8 \pm 0.2 \) as shown in §6.3 and we discuss the results and implications of our observations in §6.4.

### 6.2 VLT spectroscopy

On 18 December 1999, at 4:19 UT, low-resolution spectra of the optical counterpart of GRB991216 were acquired with the *FOcal Reducer and low-dispersion Spectrograph* (FORS1), mounted at Antu, the first unit 8-m telescope of the VLT at the European Southern Observatory (ESO) on Paranal, Chile. The spectra consist of six 600 second exposures taken with the grism G150I (three exposures without and three with order separation filter, which avoids contamination redwards of 6500 Å), giving a useful wavelength coverage of about 3800–8300 Å, and a spectral resolution of roughly 22 Å. The slit (width×length = 1″×7″) was positioned on the optical afterglow at the parallactic angle. The seeing varied between 0′.5 and 0′.6 during the observations. The spectra were bias-subtracted and flat-field corrected using IRAF (Tody 1993) using standard methods. After removing the cosmic rays, the spectra were optimally extracted (Horne 1986) from the summed images. The sky lines were removed by fitting for each column the median values of two 15-pixel regions near the object spectrum, one above and one below. The extracted spectrum was wavelength calibrated with a Helium-Neon-Argon lamp spectrum, and flux calibrated using a spectrum of the spectrophotometric standard HD49798.

The red part of the spectrum was increased by 5% (2.5% of which is due to the fading of the afterglow), to smoothly connect the two halves into one spectrum at 6200 Å. We then applied the Galactic extinction correction with a value of \( E(3-V) = 0.58 \) (Schlegel et al. 1998) and scaled the absolute zeropoint of the spectrum to our V, R and I extinction-corrected photometry values (Rol et al. 2002, in prep.) at the same epoch as the spectrum, yielding an absolute flux calibration (Fukugita et al. 1995). We find the scaling factor, which is due to slit losses, to be \( 1.94 \pm 0.06 \). Its 3% scatter is an indication of the relative error of the spectrophotometry between 5500 Å and 8000 Å. The spectrum is shown in Fig. 6.1.

The two strong features in the red spectrum around 6900 Å and 7600 Å are caused by the earth's atmosphere and are not intrinsic to the GRB host. In the blue part of the spectrum, several absorption lines are securely detected. From inspection of the standard star spectrum at the same wavelengths we can conclude that the detected lines are not caused by the instrument, nor by the earth's atmosphere. The detected lines cannot be identified with typical inter-stellar medium (ISM) absorption features of a system at a single redshift; at least three systems need to be invoked. An alternative explanation is that the feature around 5700 Å is Ly\( \alpha \) at \( z = 3.6 \), and that the features shortward of it are Ly\( \alpha \) forest lines. We have simulated such a spectrum, and the lines
Figure 6.1: *Top panel:* the optical spectrum of the afterglow of GRB 991216, taken 1.5 days after the burst. The instrumental resolution is roughly 4 pixels, corresponding to 22 Å. The spectrum has not been smoothed. The blue and red spectra (respectively without and with order separation filter) are connected at 6200 Å. The two strong absorption lines longward of 6000 Å are telluric. *Bottom panel:* a blow-up of the top spectrum, over the wavelength ranges 4000–6000 Å and 7800–8200 Å. For the latter range, we also plot the combined blue and red spectra, normalized at 80 μJy for comparison with the red spectrum. We have identified several strong rest-frame UV absorption features, which are indicated with short solid lines. Based on the inferred redshifts of these features, there seem to be numerous weaker lines, indicated with short dashed lines. The lower line identification labels correspond to the $z = 1.02$ system, the middle ones to $z = 0.80$ and the top ones to $z = 0.77$ (see also Table 6.1). For both panels, the Poisson error spectrum is also plotted.
Table 6.1: Identification of the securely detected absorption lines in the VLT spectrum taken around 1999 December 18:18 UT, i.e. 1.51 days after the burst. The columns list the observed wavelength and observed equivalent width, the identification and corresponding redshift. In parentheses we list the estimated Poisson error contribution to the equivalent width measurements, which is not included in the errors listed. Note that the observed equivalent width needs to be divided by \((1+z)\) to obtain the rest-frame equivalent width.

<table>
<thead>
<tr>
<th>(\lambda_{\text{obs}}) (Å)</th>
<th>(W_{\text{obs}}) (Å)</th>
<th>ID</th>
<th>(z_{\text{abs}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4587</td>
<td>6.6^{+1.0}_{-0.9} (1.3)</td>
<td>FeII (\lambda 2600)</td>
<td>0.764</td>
</tr>
<tr>
<td>4689</td>
<td>6.2^{+1.0}_{-0.9} (1.1)</td>
<td>FeII (\lambda 2600)</td>
<td>0.803</td>
</tr>
<tr>
<td>4957</td>
<td>7.0^{+1.4}_{-1.0} (0.8)</td>
<td>MgII (\lambda 2800)</td>
<td>0.770</td>
</tr>
<tr>
<td>5047</td>
<td>11.0^{+1.2}_{-1.2} (0.7)</td>
<td>MgII (\lambda 2800)</td>
<td>0.803</td>
</tr>
<tr>
<td>5662</td>
<td>6.6^{+1.1}_{-0.9} (0.6)</td>
<td>MgII (\lambda 2800)</td>
<td>1.022</td>
</tr>
</tbody>
</table>

We measure the equivalent width (EW) of the five significant detections as follows, using the *splot* routine in IRAF. By eye, we fit the continuum three times with a high-order polynomial function: once such that the polynomial passes through the upper part of the continuum, once through the lower part, and once through the middle. After normalization, we measure the EWs with the *e* option, which sums up the EW in between the borders indicated with the cursor. We take the "central" EW as the best estimate, and use the upper and lower continuum fit values as the upper and lower error estimates. These observed EWs are listed in Table 6.1, along with their central wavelengths, identification and corresponding redshift. We also list in parentheses the estimated Poisson error contribution in the equivalent width measurement. To obtain the equivalent width in the rest frame, the observed EWs in Table 6.1 need to be divided by \((1+z)\). On the basis of these line identifications, we indicate in Fig. 6.1 the positions of other typical ISM absorption lines, such as MgI \(\lambda 2852\), CaII H and K, and other Fe lines. In several cases a corresponding absorption feature is present.

On the basis of the identification of the strongest features (indicated with the solid lines in Fig. 6.1) we infer the presence of three absorption-line systems along the line of sight, with the following redshifts: \(z = 0.77\), \(z = 0.80\) and \(z = 1.02\). The significance of the \(z = 1.02\) system in the blue part of the spectrum is strengthened by the identification of CaII H and K around 8000 Å, respectively at \(z = 1.021\) and \(z = 1.022\). To increase the signal-to-noise around the possible Ca lines, we have added the blue to the red
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spectrum, even though the blue spectrum is contaminated with light from the second order redwards of 6500 Å. This second order appears with twice the resolution and at twice the wavelength of the first order. Due to the low sensitivity of the CCD below 3700 Å, the second order is not expected to set in until 7400 Å. We normalized the resulting combined spectrum to 80 μJy, which is also shown in Fig. 6.1. In the combined spectrum we do not detect any possible lines from 6200–9000 Å, other than the two possible CaII features, the atmospheric lines, and the feature around 6290 Å, which is also visible in the red spectrum only. We believe that the CaII H and K lines are not due to contamination with shorter-wavelength features from the second order, because (i) we would have expected to see more contaminating features other than the CaII H and K lines, and (ii) their first-order wavelengths would be 3976 Å and 4009 Å, which we cannot identify with common absorption lines in any of the three absorption-line systems. Assuming there is no contamination, we measure the following equivalent widths in the combined spectrum: $\text{EW (CaII K λ3933)} = 1.7^{+0.3}_{-0.2}$ Å and $\text{EW (CaII H λ3968)} = 2.4^{+0.8}_{-0.3}$ Å, with an estimated additional Poisson error of 0.4 Å for both lines. The expected ratio of this doublet on the basis of the oscillator strengths, $\text{CaII K λ3933}/\text{CaII H λ3968}$, is roughly 2 if the lines are not saturated, but can be unity if they are saturated. The measured ratio is $0.7^{+0.3}_{-0.2}$, which would indicate that the CaII lines are saturated.

A redshift of $z = 1.02$ for GRB 991216 is consistent with the inferred $z = 1.00 \pm 0.02$ iron line detection (4.5σ) in the Chandra spectrum of the X-ray afterglow of GRB 991216 (Piro et al. 2000). This $z = 1.02$ system most likely corresponds to the host galaxy of GRB 991216. In all cases for which both GRB absorption and emission lines have been detected, the (most distant) absorption system is at the same redshift as the emission lines from the presumed host galaxy (e.g. for GRB 980703, Djorgovski et al. 1998). Moreover, if the detection of MgI at $z = 1.02$ is real, this suggests a dense environment at this redshift, probably the ISM of the host galaxy. The detection of the CaII doublet supports this, since this is believed to require column densities that are typically an order of magnitude larger than seen in MgI absorbers (Bowen 1991; Carilli & Van Gorkom 1992). As we discuss in §6.4, almost all GRB afterglows for which rapid spectroscopy was performed show MgI in absorption at the host-galaxy redshift, the latter being confirmed by the detection of emission lines in four cases (see Table 6.2). The $z = 0.80$ system contains the strongest MgII and FeII features, which may be indicative of a galaxy along the line of sight denser than the GRB host galaxy itself.

### 6.3 HST imaging

The field of GRB 991216 (Kippen et al. 1999; Uglesich et al. 1999) was observed with HST/STIS approximately 4 months after the burst, on 17 April 2000, starting at 11:36 UT, through the clear (50CCD) and long pass (LP) filters, each for a total of 4790
6.3 HST imaging

Figure 6.2: The sum of the HST/STIS 50CCD and LP images of the field of GRB 991216. The position of the early optical transient is marked with a black circle, with an error radius of 0\textquotesingle 05 (2 drizzled HST pixels). Based on the tentative identification of three absorption-line systems in the spectrum, we believe A to be the host galaxy of GRB 991216 at $z = 1.02$, and B to be responsible for the absorption lines at $z = 0.80$. Either one of the galaxies that are located 2\textquotesingle to the SE and NW of the transient position could be the counterpart of the $z = 0.77$ system. A valid alternative is that A and B are part of the same host, possibly two systems in the process of merging, and that the $z = 0.80$ system is too faint to be detected in our images.

seconds. The pipeline reduced images were drizzled (see Fruchter & Hook 2002) onto output images with pixels one-half native scale, or approximately 0\textquotesingle 025 on a side. Fig. 6.2 shows the central 5\times5 square arcseconds of the sum of the 50CCD and LP images.

We have projected the OT position from an early VLT image, taken 1.5 days after the burst, to the frame of the HST drizzled images. Four bright nearby reference stars were used, and the estimated 1\sigma error in the resulting position is 0\textquotesingle 05, corresponding to 2 drizzled pixels. The position and its error are indicated with a circle in Fig. 6.2. The error circle coincides with one of two faint regions of light (A and B), which are separated by 0\textquotesingle 6. A and B are possibly part of the same galaxy, or they could be two systems that are interacting. Such a merging system as GRB host is not unexpected:
merging systems are known to produce bursts of star formation, where one can expect GRBs produced by the collapse of massive stars. Several other host galaxies also show a disturbed morphology, e.g. the host of GRB 990123 (Fruchter et al. 1999c).

However, the VLT spectrum suggests the presence of a system at $z = 0.80$ along the line of sight (see § 6.2 and § 6.4), which allows for the possibility that A and B are not belonging to the same system, but that B is actually a foreground system and that A is the host galaxy of GRB 991216. The spectrum shows a hint of MgI at $z = 0.80$ which, if real, would probably require a foreground system to be very close to the line of sight, such that relatively dense regions of the absorption system are being probed. This is consistent with the HST image if B is a foreground galaxy. The two galaxies are about equally bright in the 50CCD as in the LP image, showing that they have similar colours with most of the light coming out longward of 5500 Å. Galaxy A appears to be irregular, with a diameter of about 0\,"3. Either one of the two other galaxies that are located roughly 2\," away from the OT position could be responsible for the absorption system at $z = 0.77$. At a redshift of 0.77, 2\," corresponds to about 14 kiloparsec (assuming $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega\Lambda = 0.7$), which is smaller than the typical galaxy halo size, and so one would expect to see MgII in absorption.

Using an aperture of diameter 0\,"4, we measure $R = 26.9 \pm 0.2$ for A, while B has $R = 26.1 \pm 0.2$ inside an aperture of diameter 0\,"6. It is likely that the total magnitudes of these galaxies are underestimated by at least a couple of tenths due to the small apertures used. Halpern et al. (2000) measure $R = 24.8 \pm 0.1$ within an aperture of diameter 2\,\"2 around the OT position in a 1\," seeing Keck image of 2000 April 4 UT. To check if our calibration is consistent with the ground-based photometry, we measured the total light of A and B around the OT position with the same aperture diameter as Halpern et al. (2000), and find $R = 24.8 \pm 0.2$.

The transient afterglow may still be present in these observations, but the low signal to noise ratio does not allow an unambiguous identification of the bright patch at the edge of the galaxy as a point source. We estimate that any remaining OT is not brighter than $R = 27.6$. Assuming the single power law decay index, $\alpha = -1.36$, of Garnavich et al. (2000), the expected magnitude of the afterglow at the time of our observations is $R \sim 27$. Our observations are therefore consistent with the break in the light curve reported by Halpern et al. (2000). A supernova of type SN1998bw at a redshift of $z = 1.02$ would have $R > 30$ at the epoch of our observations, and would thus be too faint to be detected.
6.4 Discussion

The combination of the VLT spectroscopy and HST imaging results leads us to conclude, albeit speculatively, that galaxy A is the likely host galaxy of GRB 991216, at a redshift of $z = 1.02$, and that galaxy B probably is a foreground galaxy at $z = 0.80$. An alternative explanation, which we cannot rule out, is that A and B are part of the same galaxy at $z = 1.02$, or in the process of merging, and that the absorption system at $z = 0.80$ is either not detected in emission, or that one of the two galaxies at $2''$ is the counterpart of this system. The possible detection of the CaII doublet at $z = 1.02$ argues in favour of the latter scenario, since (at low redshifts) the CaII lines are detected mainly in disrupted environments (Bowen 1991; Carilli & Van Gorkom 1992). A third possibility is that A and B are both foreground systems, and that the host galaxy is not detected. One of the other galaxies separated about $2''$ from the afterglow position could be responsible for a third absorption-line system at $z = 0.77$. The proposed configuration can be confirmed by the detection of emission lines from galaxies A and B.

Up to March 2001 (i.e. including GRB 010222), there are nine GRBs for which early spectra were acquired and absorption lines were detected. Table 6.2 lists for each of these GRBs: the redshift, the identified host-galaxy absorption lines, and the lines identified in foreground systems along the GRB sight line. In almost all spectra MgI $\lambda$2853 is detected, which is indicative of a low-ionization, dense interstellar medium, probably approaching and possibly even exceeding column densities of Damped Ly$\alpha$ Absorbers (DLAs), which have $N_{HI} > 2 \times 10^{20}$ cm$^{-2}$. Hence the early spectral observations of GRB afterglows tend to favor the 'collapsar' model (Woosley 1993), where GRBs are expected to occur in dense star-forming regions. In case of the neutron star binary merger model, at least some burst spectra would not show MgI due to the kick velocity received at birth, which is likely to move the system to an ISM where the Mg atoms are completely ionized.

What is the probability of finding intervening metal absorption-line systems along the line of sight to a GRB? This number can be estimated from quasar absorption-line studies. We assume that the systems that we tentatively found, have column densities typical of Lyman limit systems, i.e. $N_{HI} > 1.6 \times 10^{17}$ cm$^{-2}$. These systems are well-probed by MgII absorption features, as shown by Steidel & Sargent (1992). MgI is easily ionized, and MgII dominates in regions that are less dense, where the ionizing radiation can penetrate, e.g. in galaxy halos. We use the number of Lyman limit systems per unit redshift as observed by Storrie-Lombardi et al. (1994): $n(z) = (0.27^{+0.20}_{-0.13}) (1+z)^{(1.55^{+0.45}_{-1.30})}$. The number of expected systems along a GRB line of sight is found by integrating $n(z)$ over the effective redshift coverage, i.e. from the lowest redshift where a system could have been detected to the redshift of the GRB. For the minimum redshift we adopt $z = 0.4$ (MgI $\lambda$2853 at 4000 Å). We then expect to find $5.4^{+4.0}_{-2.9}$ Lyman limit systems in the entire GRB sample. When using the numbers from Møller & Jakobsen (1990):
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<table>
<thead>
<tr>
<th>MgII/AHα z = 0.927</th>
<th>MgII/AHα z = 0.77</th>
</tr>
</thead>
<tbody>
<tr>
<td>none 11.12 ± 13.28, and possibly 9.10</td>
<td>none 6</td>
</tr>
<tr>
<td>none 7.8</td>
<td>5</td>
</tr>
<tr>
<td>none 3.4</td>
<td>2</td>
</tr>
<tr>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

MgII/AHα z = 0.76

**Table 6.2:** Absorption lines detected in early-time spectra of GRB afterglows through GRB 010222. References: I. Meléndez
\[ n(z) = 0.76(1+z)^{0.68}, \]

the resulting number of systems is 9.0, which is consistent with the estimate above. Table 6.2 lists the sample of bursts (that occurred before March 2001) for which rapid spectroscopy was performed and lines were detected. There are three bursts for which foreground systems were found: GRB 970508, GRB 991216 and GRB 010222. With the systems at \( z = 0.77 \) and \( z = 0.80 \), the total number of foreground systems is five, i.e. consistent with the expected number from QSO lines of sight.

We have presented a low-resolution spectrum of GRB 991216, taken 1.5 days after the burst, from which we have inferred the possible presence of three metal absorption-line systems. If the identification of galaxy B with \( R = 26.1 \pm 0.2 \) at a redshift of \( z = 0.80 \) is real, this would be one of the faintest imaging detections compared to absorption-line systems discovered in QSO lines of sight. Although higher spectral resolution is needed to study future hosts and possible foreground systems in detail, our observations hint at the potential that GRBs offer to study not only the host, but also intervening systems in absorption as well as in emission.

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