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The galaxies in the field of the nearby GRB 980425/SN 1998bw

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ABSTRACT

We present spectroscopic observations of ESO 184-G82, the host galaxy of GRB 980425/SN 1998bw, and six galaxies in its field. A host redshift of $z = 0.0087 \pm 0.0006$ is derived, consistent with that measured by Tinney et al. (1998, IAU Circ., 6896). Redshifts are obtained for the six surrounding galaxies observed. Three of these galaxies lie within 11 Mpc of each other, confirming the suggestion that some of these galaxies form a group. However, all of the field galaxies observed lie at significantly greater distances than ESO 184-G82 and are therefore not associated with it. The host galaxy of GRB 980425/SN 1998bw thus appears to be an isolated dwarf galaxy and interactions with other galaxies do not seem to be responsible for its star formation.

Key words. galaxies: individual: ESO 184-G82 – gamma rays: bursts – supernovae: individual: SN 1998bw

1. Introduction

Gamma-Ray Burst GRB 980425 was detected by *BeppoSAX* (Soffitta et al. 1998) and with the Burst and Transient Source Experiment (BATSE, Kippen 1998). It is most notable for its co-incidence in both space and time with SN 1998bw (Galama et al. 1998), a very energetic Type Ic supernova (Patat et al. 2001). The probability of a chance co-incidence of GRB 980425 and SN 1998bw has been estimated to be $\sim 10^{-4}$ (Galama et al. 1998). Therefore this detection provided the first convincing evidence for the link between long-duration GRBs and SNe, one which has subsequently been confirmed with the direct detection of SN 2003dh associated with GRB 030329 (Hjorth et al. 2003; Stanek et al. 2003). This case lent particular weight to the proposed GRB 980425/SN 1998bw connection due to the spectral similarity observed between SN 1998bw and SN 2003dh. Additional spectroscopic and photometric studies strongly support the GRB-SN connection (Della Valle 2005; Matheson 2005; Fynbo et al. 2004). Examples include the unambiguous association of SN 2003lw with GRB 031203 (Malesani et al. 2004; Thomsen et al. 2004) and evidence for extra light at later times in a large proportion of GRB afterglows (Zeh et al. 2004).

Assuming this association to be true, GRB 980425 was a sub-luminous GRB, emitting an equivalent isotropic γ-ray energy of $\sim 8 \times 10^{47}$ erg (Galama et al. 1998), less luminous than typical GRBs by a factor of 10^4. It occurred in a spiral arm of ESO 184-G82, at a redshift of 0.0085 ± 0.0002 (Tinney et al. 1998). This makes GRB 980425 by far the closest GRB detected to date, the next closest being GRB 031203 at a redshift of $z = 0.1055$ (Prochaska et al. 2004). Given such relative proximity, GRB 980425 provides a rare and excellent opportunity for further study of the host's galaxy field.

Hubble Space Telescope (HST) imaging of ESO 184-G82, as undertaken by Fynbo et al. (2000), indicates that the host has a high specific star-formation rate. This has recently been confirmed by Sollerman et al. (2005). Attention is drawn to the local environment of ESO 184-G82, showing a number of galaxies lying in apparent close proximity to the GRB host (see Fig. 1). ESO 184-G82 has been considered to be a member of this group of galaxies including ESO 184-G80 and ESO 184-G81 (Holmberg et al. 1977). If these galaxies lie at distances comparable to that of ESO 184-G82, the star-formation rate of the host galaxy, and hence the probability of a GRB event, may have been enhanced by interaction with these galaxies.

In this paper we present optical spectroscopy of ESO 184-G82 and six field galaxies in its vicinity. The paper is organised as follows: Observations and data reduction procedures are described in Sect. 2. Section 3 presents the results of our investigation into the host's environs and Sect. 4 discusses the conclusions and implications of our results.

2. Observations and data reduction

Spectroscopic observations were undertaken of the host and six galaxies in its field, as marked in Fig. 1. The field galaxies

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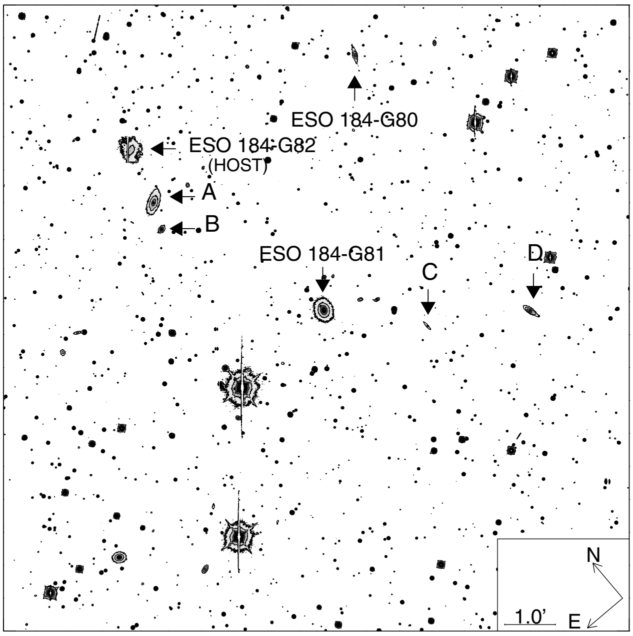

Fig. 1. DFOSC *R*-band field surrounding GRB 980425 (13.7′ × 13.7′ FOV). Galaxies for which spectroscopic observations were carried out are marked (see Table 1).

include ESO 184-G80, ESO 184-G81 and four previously unclassified galaxies, labelled A to D with increasing angular distance from the host.

The field galaxies were observed using the Danish 1.54 m telescope at La Silla, Chile. The Danish Faint Object Spectrograph and Camera (DFOSC) was mounted on the telescope with grism # 7 for all observations, resulting in a spectral range of 3800–6800 Å. The slit width was varied between 2.5″ and 2.0″ giving a spectral resolution of ∼10 Å and ∼8 Å, respectively, measured from the typical FWHM of an arc spectrum emission line. In most cases, the slit was aligned so as to include two of the sample galaxies. The detector used was a 2k × 2k Loral CCD with a gain of 1.3 e^- ADU^{-1}, read-out noise of 7.5 e^- and pixel scale of 0.40″ $pixel^{-1}$. The DFOSC field of view (FOV) is 13.7′ × 13.7′. In order to measure the redshift of the host galaxy we used the VLT spectra obtained on June 13, 1999 by Sollerman et al. (2000). These observations were carried out using the FORS1 instrument. Grism 300V was used, giving a wavelength range of 3600−9000 Å. The width of the slit was 1″ giving a spectral resolution of ∼7 Å. The gain and read-out noise of the CCD were set to 0.34 e^- ADU^{-1} and 5.75 e^-, respectively. These data are also available in the ESO archive.

Zero-exposure bias frames and flat-field exposures were taken on each observing night. Spectral images of He-Ne arc lines were obtained immediately before and subsequent to the object exposures under identical observing conditions for the Danish 1.54 m observations. For the stable VLT/FORS1 instrument, we used arc images obtained in the morning as part of the usual calibration plan. For the VLT/FORS1 observations of the host galaxy, we also performed observations of the standard star LTT 7379. Spectroscopic standard star observations were not obtained for the field galaxies. Thus, the DFOSC spectra are not calibrated in flux (see panels (b–g) of Fig. 2), which is irrelevant for our purposes. A log of the observations is shown in Table 1.

Data reduction was performed as standard using IRAF V2.12.2[1]. Frames were bias and overscan-subtracted in order to remove the pedestal bias level and any underlying pixel structure. Flat-field frames were divided into the object and arc frames to eliminate pixel-to-pixel sensitivity variations. The object spectra were then extracted to 1-D images of pixel number against ADU $pixel^{-1}$. A variance-weighted extraction was chosen to remove random cosmic ray events. In order to wavelength calibrate the pixel scale, calibration spectra were extracted from the arc lamp images and a dispersion scale determined from the known wavelengths of a number of Hg-He-Ar/He-Ne emission lines. Dispersion scales were assigned to object spectra by taking an average of those arc spectra solutions from the calibration exposures nearest in time to the object exposures. The typical rms of the dispersion fit ranged from 0.01 Å to 0.1 Å. The accuracy of the wavelength calibration was verified by identifying the wavelengths of prominent sky lines for each night. The observed deviations are consistent with the above rms scatter. No systematic variations in the wavelength scale from night to night were observed. A flux calibration was performed for the host galaxy using the observed flux of the spectrophotometric standard LTT 7379.

3. Analysis

The redshift of each galaxy was determined using two methods (see Table 2). An initial determination of the redshift was made using the IRAF task *rvidlines*. This requires the identification of a prominent spectral feature to which a Gaussian function is fit. Based on the central wavelength of this line and an input list of known spectral lines, other features at a consistent redshift are identified. A weighted average redshift value and corresponding error based on the Gaussian fit is output.

An alternative measurement of each redshift was obtained using the Fourier cross-correlation method as described by Tonry & Davis (1979) using the IRAF task *fxcor*. In this analysis, each galaxy spectrum was cross-correlated with template spectra obtained from Kinney et al. (1996). These spectra are characterised by high S/N ratios and are de-redshifted to the rest frame. Template spectra for bulge, elliptical, S0, Sa, Sb (absorption-line dominated) and Sc (emission-line dominated) galaxy morphologies were used. *Fxcor* determines the wavelength shift of the object spectrum at the point of maximum correlation and computes a redshift value. The task outputs redshift errors based on the height of the correlation peak and noise statistics.

Combined spectra for each galaxy observed are shown in Fig. 2. Table 2 gives the heliocentric redshifts determined in each case using the *fxcor* and *rvidlines* methods discussed above. Through the use of a number of templates for correlation with the absorption spectra, a mean value for the redshift was determined for a given galaxy spectrum, weighted by the

[1] Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories (NOAO).

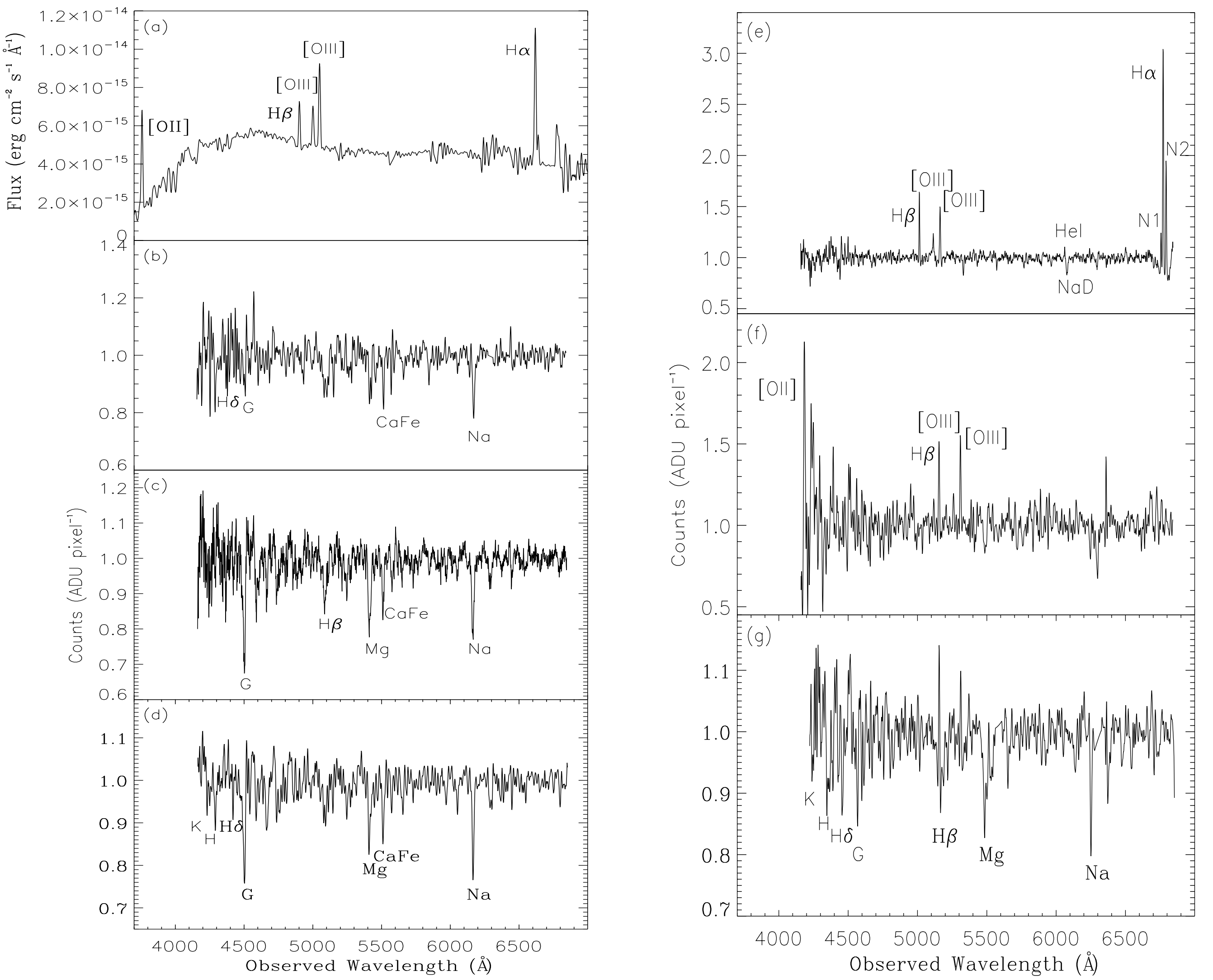

Fig. 2. Spectra of **a)** ESO 184-G82, the host of GRB 980425 and galaxies in its field; **b)** ESO 184-G80; **c)** ESO 184-G81; **d)** Galaxy A; **e)** Galaxy B; **f)** Galaxy C; and **g)** Galaxy D. The VLT spectrum of the host **a)** is flux-calibrated while the DFOSC spectra (**b)**−**g)**) are normalised to a flat continuum. The spectral lines used in the redshift determination for each galaxy are labelled.

square inverse of the *fxcor* error. The *fxcor* errors from each template are added in quadrature to produce the *fxcor* error quoted in Table 2. A consistent value of $\sigma = 0.0004$ for the standard deviations of the independent cross-correlations was obtained for each galaxy. The spectrum obtained for Galaxy C proved too weak for an accurate *fxcor* redshift determination.

In the case of an emission-line dominated spectrum, the *rvidlines* redshift is adopted, since the emission features are unambiguous and well fit by a Gaussian function. For the absorption-line spectra, we view the *fxcor* redshift as being the more reliable method, as it proved difficult to fit Gaussians to the absorption lines. In such cases *rvidlines* was used to verify the authenticity of the chosen correlation peak. The *rvidlines* error in Table 2 is an internal error generated by the task based solely on the Gaussian fit to a single spectral feature and so is significantly underestimated. We therefore assume a conservative error of 0.0006 for all redshifts based on the template redshift deviations and the *fxcor* errors.

The redshift difference between the host galaxy and the bright galaxies in its field corresponds to a velocity difference of 6000 km s^{-1}, while the typical velocity dispersion observed in low redshift galaxy clusters is at most 1000 km s^{-1} (Desai et al. 2004). We therefore conclude that ESO 184-G82 is an isolated dwarf galaxy in a state of active star-formation, the origin of which is not attributable to any obvious interaction with its local environment. Having a velocity dispersion of ~300 km s^{-1} and lying within 11 Mpc of each other, ESO 184-G81, ESO 184-G80 and Galaxy A are most likely located in a small group, but are not near to the host galaxy.

4. Are GRB hosts in underdense regions?

Extensive HST imaging studies of GRB host galaxies have been undertaken (e.g. Conselice et al. 2005). In one such study of 42 galaxies, a large proportion of those observed

Table 1. Log of observations.

Telescope/Grism	Object	Date	Exposure time (s)	Seeing (″)
VLT/300V	ESO184-G82	13-06-1999	4 × 1800	
D 1.54m/# 7	ESO 184-G80	24-08-2000	3 × 1200, 1 × 1050	1.8
		30-08-2000	6 × 1200	1.2
	ESO 184-G81	27-08-2000	5 × 1200	1.4
		28-08-2000	7 × 1200	1.6
		01-09-2000	4 × 1200	1.4
	Galaxy A	26-08-2000	2 × 1200, 1 × 1118	2.3
		29-08-2000	6 × 1200	1.6
		02-09-2000	5 × 1200	1.0
	Galaxy B	26-08-2000	2 × 1200, 1 × 1118	2.3
		29-08-2000	6 × 1200	1.6
		02-09-2000	5 × 1200	1.0
	Galaxy C	27-08-2000	5 × 1200	1.4
		30-08-2000	6 × 1200	1.2
	Galaxy D	28-08-2000	7 × 1200	1.6
		01-09-2000	4 × 1200	1.4

Table 2. Heliocentric-corrected redshifts for galaxies in the field of GRB 980425 as marked in Fig. 1.

Galaxy	Redshift (*fxcor*)	Redshift (*rvidlines*)
ESO 184-G82	0.0085 ± 0.0003	0.00867 ± 0.00004
ESO 184-G80	0.0470 ± 0.0007	0.0470 ± 0.0002
ESO 184-G81	0.0448 ± 0.0007	0.0452 ± 0.0001
Galaxy A	0.0447 ± 0.0007	0.0448 ± 0.0003
Galaxy B	0.0314 ± 0.0003	0.0317 ± 0.00002
Galaxy C	undetermined	0.0609 ± 0.0001
Galaxy D	0.0605 ± 0.0006	0.0604 ± 0.0002

(∼30−60%) show evidence for interaction (Wainwright et al. 2005). Analysis of the environments of four GRB hosts identify several galaxies at a similar redshift in all cases (Fynbo et al. 2002; Jakobsson et al. 2005). GRB 980613 also occurred in a host galaxy which appears to be part of a complex, interacting system (Hjorth et al. 2002) as is the host of GRB 001007 (Castro Cerón et al. 2002). However, it is not known if any of these fields are overdense.

Whether GRBs preferentially occur in galaxy-dense regions remains uncertain, but the evidence seems to hint that they do not. Photometric redshifts have been determined for galaxies in the field of GRB 000210 showing that there is no obvious grouping of galaxies around the host (Gorosabel et al. 2003). In a study of the cross-correlation between GRB host galaxies and the surrounding galaxy environments, Bornancini et al. (2004) found tentative evidence that GRB host galaxies are more likely to be located in low density galaxy environments. It has been suggested that objects found in lower-density galaxy regions may also tend to be sub-luminous (Le Floc'h et al. 2003), consistent with ESO 184-G82 in particular and GRB host characteristics in general. The GRB 030329 host at $z = 0.1685$ (Greiner et al. 2003) may be a counter-example, having at least one field galaxy at $z \sim 0.171$ and hence being consistent with a potential clustering (Gorosabel et al. 2005).

We can now conclude that ESO 184-G82, generally regarded as being part of a galaxy group, appears in fact to be isolated and that interaction with nearby galaxies can be eliminated as a source of its high specific star-formation rate. Interestingly, in a recent study, Sollerman et al. (2005) find that the host galaxy properties are consistent with a constant star-formation rate over a few Gyr. Therefore, it seems that the present state of the galaxy is not that of a starburst and hence that the current star-formation activity does not necessarily require an external trigger.

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