The low-extinction afterglow in the solar-metallicity host galaxy of γ-ray burst 110918A *

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ABSTRACT

Galaxies selected through long γ-ray bursts (GRBs) could be of fundamental importance when mapping the star formation history out to the highest redshifts. Before using them as efficient tools in the early Universe, however, the environmental factors that govern the formation of GRBs need to be understood. Metallicity is theoretically thought to be a fundamental driver in GRB explosions and energetics, but is still, even after more than a decade of extensive studies, not fully understood. This is largely related to two phenomena: a dust-extinction bias, that prevented high-mass and thus likely high-metallicity GRB hosts to be detected in the first place, and a lack of efficient instrumentation, that limited spectroscopic studies including metallicity measurements to the low-redshift end of the GRB host population. The subject of this work is the very energetic GRB 110918A (E,iso = 1.9 × 10⁵⁵ erg), for which we measure a redshift of z = 0.984. GRB 110918A gave rise to a luminous afterglow with an intrinsic spectral slope of β = 0.70, which probed a sight-line with little extinction (Aα = 0.16 mag) and soft X-ray absorption (N_H = (1.6 ± 0.5) × 10²² cm⁻²) typical of the established distributions of afterglow properties. Photometric and spectroscopic follow-up observations of the galaxy hosting GRB 110918A, including optical/NIR photometry with GROND and spectroscopy with VLT/X-shooter, however, reveal an all but average GRB host in comparison to the z ~ 1 galaxies selected through similar afterglows to date. It has a large spatial extent with a half-light radius of R₁/₂ ~ 10 kpc, the highest stellar mass for z < 1.9 (log(M*/M☉) = 10.68 ± 0.16), and an Hβ-based star formation rate of SFR_Hβ = 41+28−16 M☉ yr⁻¹. We measure a gas-phase extinction of A_V = 1.8 mag through the Balmer decrement and one of the largest host-integrated metallicities ever of around solar using the well-constrained ratios of [NII]/Hα, and [NII]/[OII] (12 + log(O/H) = 8.93 ± 0.13 and 8.85[+0.14][-0.1]), respectively. This presents one of the very few robust metallicity measurements of GRB hosts at z ~ 1, and establishes that GRB hosts at z ~ 1 can also be very metal rich. It conclusively rules out a metallicity cut-off in GRB host galaxies and argues against an anti-correlation between metallicity and energy release in GRBs.

Key words. Gamma-ray burst; general, Gamma-ray burst; individual: GRB 110918A, ISM: general, Galaxies: abundances, Galaxies: photometry, Galaxies: star formation

1. Introduction

During their prompt emission, long gamma-ray bursts (GRBs) are the brightest objects in the Universe, easily reaching isotropic-equivalent luminosities as high as ~ 10⁵⁴ erg s⁻¹. Their observed association to supernovae events (e.g., Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Matheson et al. 2003; Della Valle 2011; Hjorth et al. 2012) has tightly linked them to the death of massive stars. The GRB itself is then believed to result from accretion of matter onto the newly formed black hole or compact object in the collapsar model (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999). The lack of hydrogen and helium in the spectra of GRB-
supernovae classify them as type Ic, supporting the notion that GRB progenitors are likely Wolf-Rayet like stars (for a review of supernova classifications see, e.g., Filippenko 1997). Given that these type of stars undergo vigorous mass loss from stellar winds, metallicity constraints ($Z < 0.3Z_\odot$) on the progenitor are postulated to ensure that an accretion disk is still formed around the black hole (Hirschi et al. 2005; Yoon & Langer 2005; Woosley & Heger 2006).

The possible association of long GRBs with massive stars supported the idea that they could be used as complementary and independent tracers of star formation, especially at high redshifts ($z \gtrsim 4$), due to their very high luminosities (see, e.g., Daigne et al. 2006; Li 2008; Kistler et al. 2009; Ishida et al. 2011). However, to have full confidence in these studies the intrinsic evolutionary effects in long GRB production must be understood and the galactic environments preferred by the progenitor need to be quantified (e.g., Butler et al. 2010; Wang & Dai 2011; Salvaterra et al. 2012; Robertson & Ellis 2012; Elliott et al. 2012). Of particular interest is the relation between the galaxies selected by GRBs and the star formation weighted population of field galaxies. To be direct and unbiased tracers of star formation, the relative rates of GRBs in galaxies of various physical properties should be the same in galaxies taken from samples that trace the global star formation density at a given redshift. Studies based on these galaxy samples are most commonly performed at $z \lesssim 1.5$, where the star formation of field galaxies is largely recovered by state-of-the-art deep-field surveys.

Initial work showed that many long GRB host galaxies had a low mass, low metallicity, as well as blue colours and were actively star forming (see, e.g., Fruchter et al. 1999; Le Floc’h et al. 2003; Berger et al. 2003; Christensen et al. 2004; Tanvir et al. 2004). This seemed directly in line with the requirements of the collapsar model. Further work carried out with larger samples (e.g. Savaglio et al. 2009), showed again similar characteristics. However, at a given mass and star formation rate, long GRB hosts were also found to be different to the normal population of star forming galaxies at the same redshift (Mannucci et al. 2011). However, these initial studies neglected the contribution from galaxies hosting dust-extinguished afterglows, often termed dark bursts (e.g., Perley et al. 2009; Greiner et al. 2011). Galaxies hosting dark bursts are systematically more massive and have a higher dust-content than the previously-established population localized with optically bright afterglows (Krühler et al. 2011; Hjorth et al. 2012; Rossi et al. 2012; Perley et al. 2013; Christensen et al. 2017; de Ugarte Postigo et al. 2012). Despite the inclusion of this more evolved galaxy population, there are still less GRBs in massive galaxies than expected based on their contribution to the overall star formation rate (SFR), at least at $z < 1.5$ (Perley et al. 2013), indicative of a GRB explosion mechanism dependent on metallicity. It is however important to note that these above conclusions are inferred indirectly through stellar mass as a metallicity proxy, and while the photometric samples of GRB hosts have reached integrated number statistics of 100 and above (e.g., Hjorth et al. 2012; Perley et al. 2013), the most crucial measurement of gas-phase metallicity has only been performed in a hand-full cases at $z \gtrsim 1$. (Levesque et al. 2010a; Krühler et al. 2012a).

Only a few host galaxies with substantial gas-phase metallicities around or above solar (e.g., Levesque et al. 2010b) that directly violate the proposed cut-off in galaxy metallicity have been observed to date. There is thus still lively debate in the literature about the nature of GRB hosts, and their relation to the star formation weighted galaxy population as a whole (e.g., Nino 2011; Mannucci et al. 2011; Kocevski & West 2011; Graham & Fruchter 2012). GRB hosts with high stellar mass and high global metallicity are hence of primary interest for GRB host studies, as they directly probe this allegedly forbidden parameter space. A robust understanding of the galactic environments in which GRBs form would then add confidence in their use as cosmological probes, beyond the limits of deep survey studies (e.g., Tanvir et al. 2012; Basa et al. 2012).

Here, we present spectroscopy and photometry of the host galaxy and afterglow of the luminous GRB 110918A, detected on the 18th of September 2011 at $T_0=21:26:57$ UT (Hurley et al. 2011). This burst had one of the highest fluences of any GRB observed over the last 20 years (together with GRB 021206; Wigger et al. 2008) and had the highest peak flux ever detected by Konus-Wind (Golenetskii et al. 2011; Frederiks et al. 2013 in prep.), located at a redshift of $z = 0.98$. The massive, metal rich host galaxy and unobscured afterglow of GRB 110918A challenges the current view of the connection between local and global environments and allow us to investigate the preferred conditions for the formation of a long GRB.

The paper is arranged as follows: first we describe the observations carried out by both ground and space based instruments and their corresponding reduction in Sect. 2. Second, the resulting properties ascertained from the SEDs and spectra of the GRB and its host are described in Sect. 3. Finally, we discuss our findings and their implications for the population of long GRBs in Sect. 4 and conclude in Sect. 5. We adopt the convention that the GRB flux density is described by $F_\nu(t) \propto t^{-\alpha} \nu^{\beta}$, reported errors are at the 1σ confidence level and we assume a ΛCDM cosmology: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$. We use a Chabrier (2003) initial mass function and abundances throughout the text.

2. Observations and Data Reduction

2.1. Swift - XRT Spectra

At the time of the IPN trigger Swift (Gehrels et al. 2004) was both in the South Atlantic Anomaly and Earth-occulted, and so no trigger (Krimm & Siegel 2011) was initiated in the Burst Alert Telescope (Barthelmy et al. 2005, BAT). However, the Swift X-ray telescope (Burrows et al. 2005) XRT began observing the field of GRB 110918A (see Fig. 1) at $T_0 + 107.4$ ks until $\approx 40$ d later. The XRT spectrum shows no signs of spectral evolution, remaining with a constant hardness ratio of $\approx 0.85$ for its entire emission. We extract a spectrum at the time interval of $T_0 + 140$ ks to $T_0 + 250$ ks to coincide with our optical/NIR wavelength observations (see Fig. 2). The XRT spectral data were obtained from the public Swift archive and were regrouped to ensure at least 20 counts per bin in the standard manner, using the groupha task from the HEAsoft package with response matrices from CALDB v20120209. We assume a Galactic hydrogen column of $N_{\text{H}} = 1.68 \times 10^{20} \text{ cm}^{-2}$ (Kalberla et al. 2005) in the direction of the burst.

2.2. GROND Optical/NIR Photometry

The Gamma-Ray Burst Optical Near-infrared Detector (GROND; Greiner et al. 2008) mounted at the MPG/ESO 2.2 m telescope at La Silla, Chile, began its follow-up campaign of GRB 110918A 29.2 hrs after the trigger simultaneously in the grriz JHK, filters (Elliott et al. 2011). A mosaic of 5 pointings was carried out to cover the full IPN error box ($\sim 20\arcmin \times 20\arcmin$) and the GRB optical afterglow candidate
Further deep observations of the host galaxy were made 392 d after the trigger with the Wide Field Imager (Baade et al. [1999] WFI), also mounted on the MPG/ESO 2.2m telescope, in the standard broadband filters BB#B/123_ESO878 (B) and BBH#1/150_ESO878 (U). Two sets of images were taken, the first on 25 October 2012 consisting of 1800 s in U and 600 s in B and the second set was on 26 October 2012, consisting of 150 s in U and 75 s in B. A calibration field was obtained on 26 October 2012 in both the U and B filters and the standard field SA113+150 was used as a primary calibrator. The photometry was carried out in the same way as the GROND images, and the magnitudes converted into the AB system using the ESO magnitude converter.

2.4. WISE IR Photometry

The Wide-field Infrared Survey Explorer (Wright et al. 2010, WISE) All-Sky Source Catalogue reveals a source at the position of the host galaxy of GRB 110918A, with an 11σ and 3σ detection in the W1 and W2 bands, centred at 3.4μm and 4.6μm respectively. The $\text{wmpro}$ magnitudes were used, which are the magnitudes retrieved from profile-fitting photometry (or the magnitude of the 95% confidence brightness) and converted into the AB system using the WISE conversion factor. Galactic reddening corrections were made using the $A_V^\text{Gal}$ conversions determined by Jarrett et al. (2012). The second spectrum of the afterglow was obtained using the OSIRIS Optical Spectroscopy (Cepa et al. 2000, OSIRIS) mounted on the 4 m Gran Telescopio Canarias (Roque de los Muchachos) starting at 13:00 UT on 21 September 2011, 2.2 d after the GRB trigger. Four exposures of 500 s each were obtained using the R400 grism and a 1′ 000′′ grating. Two of the spectra were obtained with a central wavelength of 6000 Å and the other two with 6050 Å to cover the detector gaps. In addition, a spatial dither was used to cover the amplifier boundaries. The resulting spectrum covers the range 3930 − 8170 Å. We reduced the data with tasks within the Gemini.GMOS package and IRAF v1.11, using flat field and arc lamp frames taken directly before and after the science data.

2.6. OSIRIS Optical Spectroscopy

The second spectrum of the afterglow was obtained using the Optical System for Imaging and Low Resolution Integrated Spectroscopy (Cepa et al. 2000, OSIRIS) mounted on the 10.4 m Gran Telescopio Canarias (Roque de los Muchachos) starting at 13:00 UT on 21 September 2011, 2.2 d after the GRB trig-
ger. Three exposures of 900 seconds each were taken using the R500B grism and a 1″ slit width obtained at the parallactic angle. The resulting spectrum covers the range 4400–8700 Å. Data were reduced and calibrated using standard procedures in IRAF. The spectrum was flux calibrated using G157-34 as a standard star and the 1D spectrum was scaled to the GROND afterglow photometry to correct for slit losses (correction factor of ~ 1.9).

A spectrum of the host was obtained on 11 November 2011, T₀ = 54.1 d after the GRB trigger. A sequence of three 1200 s exposures were obtained with OSIRIS using the R1000R grism and a 1.0″ slit width, covering the wavelength range of 5100 Å to 10000 Å. The spectrum was flux calibrated using the standard star G191-B2B and corrected for slit losses by scaling the 1D spectrum to the photometry of the host galaxy obtained using GROND (correction factor of ~ 3.5).

2.7. X-Shooter Optical/NIR Spectroscopy

We further observed the host of GRB 110918A with the cross-dispersed echelle spectrograph X-shooter (Vernet et al. 2011) on the Very Large Telescope Kueyen (UT2). X-shooter has three individual arms taking spectra simultaneously in the range of 3000 Å to 6500 Å (UVB arm), 5600 Å to 10 200 Å (VIS arm), and 10 200 Å to 24 800 Å (NIR arm). Three different sets of observations were carried out on 17 December 2012, 07 January 2013, and 16 January 2013, respectively, with a position angle of 59° East of North. They consisted of a pair of nodded frames with exposure times of 1200 s in each of the UVB/VIS arm and 2 × 600 s in the NIR arm. The slit width was 1.5′, 1.5″ and 0′.9 yielding a resolution measured on arc-lamp frames of R ≈ λ/Δλ = 3200, 4900, and 5300 in the UVB, VIS and NIR arm, respectively. The NIR slit includes a blocking filter for the K-band limiting our effective wavelength coverage to < 20 500 Å, but providing lower background levels in the J and H-band.

Each of the individual observations were reduced and wavelength- and flux-calibrated separately using standard procedures within the X-shooter pipeline v2.0.0 (Goldoni et al. 2006) supplied by ESO. The individual two-dimensional frames were then stacked using variance weighting in a heliocentric reference frame, and the one-dimensional spectra were extracted using an optimal extraction method. Given the extent of the target, slit-losses are substantial. Similar to the OSIRIS and GMOS spectroscopy, we scaled the well-detected continuum of the X-shooter data to the available photometric host SED. The consistency between matching factors derived from different photometric data in the individual arms⁶ provides confidence that the absolute flux-calibration in the final X-shooter spectrum is accurate to better than ~ 20% over the full wavelength range of interest.

3. Results

3.1. The Afterglow Sight-Line: Dust, Star Formation Rate and Gas

A broadband SED was constructed from the optical/NIR GROND photometry (see Sect. 2.3) at a mid time of T₀ = 194 ks and X-ray data between T₀ + 140 ks and T₀ + 250 ks. The SED was fit in a standard manner (e.g., Filgas et al. 2011), assuming that the afterglow emission is well described by the standard synchrotron mechanism. The best fit single power-law (χ²/d.o.f. = 85/73) is shown in Fig. 2, with a spectral slope of β = 0.70 ± 0.02, a hydrogen column density of N_H = 1.56 × 10²² cm⁻² and a line of sight extinction of A_V = 0.16 ± 0.06 mag, assuming SMC like dust.

![Fig. 2: Broadband SED of GRB 110918A, including optical, NIR and X-ray data. The SED was constructed using GROND data at a mid time of T₀ = 194 ks and X-ray data between T₀ + 140 ks and T₀ + 250 ks. The best-fit parameters for a power-law (χ²/d.o.f. = 85/73) are: a spectral slope of β = 0.70 ± 0.02, a hydrogen column density of N_H = 1.56 × 10²² cm⁻² and a line of sight extinction of A_V = 0.16 ± 0.06 mag, implying the improvement is not statistically significant. Nevertheless, the resulting parameters of the best fit broken power-law, as well as from different dust models, are consistent with the uncertainties of the power-law values below the break at ~ 0.6 keV and do not alter our conclusions.

Using the procedure outlined by de Ugarte Postigo et al. (2012) with the two afterglow spectra obtained with GMOS (T₀ + 1.6d) and OSIRIS (T₀ + 2.2d), we detect the transition of several metal ions including Fe II, Mg II and Mg I at a common redshift of z = 0.984 ± 0.001 (see Tables 2 and 3), consistent with galactic winds or star bursting periods (Fynbo et al. [2009], Nestor et al. [2011], Christensen et al. [2011], Rodríguez Hidalgo et al. [2012]). In comparison with a long GRB sample (de Ugarte Postigo et al. [2012]), we find that it has stronger absorption features than 80% of the sample.

3.2. The Host’s Stellar Component: Dust Attenuation, Star Formation Rate and Stellar Mass

The host of GRB 110918A was detected in 11 different filters ranging from the ultra-violet to 4.5μm, yielding a well-sampled photometric SED (see Fig. 3 and Table 1). To estimate the global properties of the host galaxy we employed standard techniques that use stellar population synthesis to estimate stellar masses, as outlined thoroughly in Ilbert et al. (2009). We con-
constructed a grid of galaxy templates based on the models taken from [Bruzual & Charlot (2003)] over a wide parameter space consisting of: a range of ages (0 – 1.35 × 10^9yr), star formation histories (∞ e', τ = 0.1, 0.3, 1, 2, 3, 5, 10, 15, 30), reddening values (E(B – V) = 0 – 0.4 mag), a single attenuation law (starburst; [Calzetti et al. 2000]) and metallicities (Z = 0.004, 0.008, 0.02). Emission lines were also included, whereby the emission lines were estimated from the predicted UV luminosity and converted to a star formation rate using [Kennicutt (1998)]. For each template a SED was constructed for the filters required and a χ^2 was calculated using the Photometric Analysis for Redshift Estimate routines, LEPhARE v2.2 ([Arnouts et al. 1999; Ilbert et al. 2006]). The best fit template was the one that gave the minimum χ^2 and the corresponding uncertainties for each parameter were obtained from the grid of χ^2 values. Systematic uncertainties of up to an average of 0.2 – 0.3 dex are expected in the stellar mass value due to the adopted stellar population models and extinction laws (see e.g., [Kruhler et al. 2011] and references therein). The filter response curves for the WI and W2 bands were obtained from [Wright et al. 2010] and for the U and B bands from the ESO web page. The results of the best fit template, which had a χ^2/# Bands = 5.4/11, had the following parameters: a mass of log(M/M☉) = 10.68 ± 0.16, a star formation rate SFRSED = 66 ± 10 M☉ yr⁻¹, a reddening of E(B – V)stars = 0.26 ± 0.15 mag, and a starburst age of τ = 0.7⁺1.4⁻0.4 Gyr.

3.3. The Host’s Gas-Phase Component: Dust Extinction, Star Formation Rate and Metallicity

The first host spectrum of GRB 110918A was obtained with OSIRIS/GTC in the optical wavelength range, ~ 50 days after the trigger, and the second one was obtained with X-shooter/VLT more than 460 days post trigger. The X-shooter spectrum extends our spectral coverage to the NIR and thus to the wavelength range where important tracers of star formation rate and metallicity are located. In summary, we clearly detect the Hα and Hβ transition from the Balmer series, as well as the forbidden transitions of [O II](λ3726, 3729) and [N II](λ6584). The emission lines corresponding to [O II](λλ4959, 5007) are cosmologically redshifted to regions of low sensitivity for both OSIRIS and X-shooter, and are thus not detected.

The velocity profile of the emission lines is clearly resolved by our X-shooter data and spans approximately 500 km s⁻¹ in velocity space (see Fig. C.1). It displays a conspicuous two-humped profile, with the two peaks of the emission lines separated by 200 km s⁻¹. However, we do not observe a spatial tilt in the line-shape as would have been expected from a largely rotationally-supported galaxy (unless it is face on), and both peaks appear at the same spatial position in the two-dimensional spectrum. Line fluxes were measured by numerically integrating the available data, and cross-checked with fitting Gaussians. Both procedures return consistent values, and from the X-shooter spectrum, we measure global emission-line fluxes of f_{[O II]} = (19.0 ± 3.1)× 10^{-17} erg s⁻¹ cm⁻², f_{Hβ} = (9.5 ± 1.9)× 10^{-17} erg s⁻¹ cm⁻², f_{4313} = (47.8 ± 4.9)× 10^{-17} erg s⁻¹ cm⁻² and f_{[N II]} = (15.3 ± 3.3)× 10^{-17} erg s⁻¹ cm⁻². The OSIRIS spectrum yields f_{[O II]} = (20.0 ± 2.8)× 10^{-17} erg s⁻¹ cm⁻², fully consistent with the X-shooter value.

Assuming case B recombination ([Osterbrock 1989] and using the standard values for electron density (10^3 cm⁻³ ≤ n_e ≤ 10^5 cm⁻³) and temperature (T_e ≈ 10^4 K), the Balmer ratio of Hα/Hβ implies an E(B – V)gas = 0.57^{+0.24}_{-0.22} or visual extinction A_V = 1.8^{+0.8}_{-0.7} on the star forming regions assuming a Milky-Way like extinction law. It is worth mentioning, that this is the luminosity-weighted reddening/extinction of the gas-phase. This value is typically found to be a factor of around two larger than the stellar E(B – V)stars from the photometric SED model (e.g., [Calzetti et al. 2000]), consistent with our measurements for GRB 110918A. The Hα line flux implies a SFR

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[7] www.cftl.hawaii.edu/~arnouts/LEPHARE/lephare.html
[8] www.eso.org/sci/facilities/lasilla/instruments/wfi/inst/filters

**Table 1: Host galaxy magnitudes.**

| Filter | Instrument | Magnitude (mag AB) | Uncertainty (mag AB) |
|--------|------------|--------------------|---------------------|
| U      | WFI        | 22.94              | 0.25                |
| B      | WFI        | 22.45              | 0.16                |
| g’     | GROND      | 22.49              | 0.15                |
| r’     | GROND      | 22.07              | 0.05                |
| i’     | GROND      | 21.26              | 0.06                |
| z      | GROND      | 20.78              | 0.06                |
| J      | GROND      | 19.92              | 0.11                |
| H      | GROND      | 19.73              | 0.17                |
| K_s    | GROND      | 19.61              | 0.22                |
| W1     | WISE       | 19.56              | 0.10                |
| W2     | WISE       | 20.28              | 0.36                |

**Notes.** Corrected for Galactic foreground reddening. The observations in g' r' i' z' JHK were obtained 36.37 d after the burst. The U B observations were obtained 392 d after the burst. The W1 and W2 photometry were obtained prior to the burst by the WISE Survey.
Table 2: Physical parameters of the galaxy hosting GRB 110918A

| Quantity                     | Unit/Method | Value   |
|------------------------------|-------------|---------|
| $E(\lambda - V)_{\text{gr}}$ | mag         | 0.05 ± 0.02 |
| $N_{HR}$                     | 10$^{14}$ cm$^{-2}$ | 1.56 ± 1.50 |
| $EW_{\text{MgII}}$ (Å)       | Mg II (2796, 2803) | 6.0 |
| $SFR_{\text{GRB}}$           | M$_{\odot}$ yr$^{-1}$ | 2.3 ± 0.7 |

Notes. All values use a Chabrier IMF, and take into account the statistical uncertainty of the measurements, as well as the uncertainty in the slit-loss and dust-correction factor if applicable. ($^{a}$) Following Nagao et al. (2006). ($^{b}$) Following Pettini & Pagel (2004). ($^{c}$) Following Kewley & Dopita (2002).

4. Discussion

4.1. Host Galaxy Identification

We have used absorption lines from metal ions in the afterglow spectrum (see also Fynbo et al. 2009) for an extensive sample, and forbidden/recombination lines from the host galaxy to determine the redshift of the GRB (see also Kührer et al. 2015), but it is in principle possible that the GRB lies at a higher redshift. To investigate if the host galaxy of GRB 110918A has been misidentified we calculate the commonly used p-value, $p(m) = 1 - \exp(-\pi^2 \sigma^2 / m)$, which is the probability of finding a galaxy of magnitude $m$ (or brighter) overlapping the GRB within an effective radius $r$, assuming that galaxies are Poisson distributed throughout the sky (Bloom et al. 2002). This neglects any type of galaxy clustering, however, recent work indicates that GRB locations do not preferentially lie in areas of strong galaxy overabundances (Cucchiara et al. 2012; Sudilovsky et al. 2013). The number of galaxies brighter than $m$ per square arcsecond is given by $\sigma$, taken from Bloom et al. (2002) and calculated from the work of Hogg et al. (1997).

The burst location of GRB 110918A is seen to be offset from the bright centroid of the host by 12 kpc, however, in comparison to the half-light radius of the host galaxy, $R_h = 10.6$ kpc, the offset is consistent with the long GRB population, which has a median offset of $R_{\text{offset}}/R_h \sim 1$ (Bloom et al. 2002). We follow Bloom et al. (2002) and set $r_i \leq 2 \times R_h = 2.66$. Synthetic $R_{\text{C}}$-band (Bessell 1979) photometry of the GRB 110918A host galaxy using the best fit galaxy template taken from Sect. 3.7 and the conversions given in (Rossi et al. 2012), results in $R_{\text{C}} = 21.7$ mag$^{-1}$ Vega. This yields a probability of chance association of $p = 0.01$, making this galaxy highly likely the host of GRB 110918A.

The non-detection of the Lyman forest above $\sim 4500 \AA$ implies a strong upper limit of $z < 2.7$. Therefore, using our knowledge of the strength of spectral features in GRB environments and their distribution (de Ugarte Postigo et al. 2012), we can estimate the likelihood of the GRB having occurred between redshift 1.0 and 2.7 and yet not having detectable absorption lines at the redshift of the host in its spectrum. We calculate the detection limits for Mg II and C IV doublets as described by de Ugarte Postigo et al. (2012) and find that the lines would have to be weaker than 99.7% of a normal long GRB sample to have happened at a redshift between 1 and 2.7. Furthermore, the properties of the absorber (strong Mg II absorption and vigorous star formation, see Sect. 3.1), are very common in other afterglow observations, and do not indicate a different physical nature. Combining the arguments presented above, we consider the redshift of the GRB, and accordingly the physical association between GRB and galaxy, robust.

4.2. Host Environment in the Context of the GRB-Host Population

The mass-metallicity relation of field galaxies (e.g., Tremonti et al. 2004) has been studied in depth to high redshift (Savaglio et al. 2005; Erb et al. 2006; Yabe et al. 2012). Similarly, the dust content of a given galaxy is also well known to correlate with stellar mass (e.g., Garn & Best 2010; Zahid et al. 2013). To illustrate the behaviour for GRB hosts, we show the average host galaxy extinction versus the stellar mass of the host galaxy alongside the correlation determined by (Garn & Best 2010) in Fig. 4. The GRB hosts are taken from Savaglio et al. (2009) (SG09), Mannucci et al. (2011) (MN11), Kührer et al. (2011) (KR11) and Perley et al. (2013) (PL13) and converted to a Chabrier IMF if need be. The correlation of (Garn & Best 2010) has been determined from SDSS galaxies with $z < 0.7$ and so we limited our GRB sample to galaxies with $z < 1.0$. GRB hosts follow the distribution obtained from field galaxies well, with a possible excess of dusty systems at stellar masses of $10^{10-10} M_{\odot}$. Given the inherent systematic difficulties of determining the dust reddening in galaxies, and the heterogeneous selection of targets (in particular the KR11 and PL13 samples were initially selected to contain a lot of dust), this trend should not be over-interpreted. What seems clear is that the host of GRB 110918A is at the high end of the distribution of stellar masses for GRB hosts, and
there is no strong discrepancy between GRB-selected galaxies and field galaxies in the relation between their dust content and stellar mass.

Secondly we plot the host’s stellar mass vs. the GRB’s line of sight extinction in Fig. 5. Perley et al. (2013) have highlighted that throughout the covered galaxy-mass scale, there is a very tight correlation between stellar-mass and sight-line extinction probed by the GRBs. Quite surprisingly, this correlation between afterglow dust and galaxy mass is found to be stronger than for any other physical property of the galaxy (PL13). From Fig. 5 it can be seen that hosts selected due to high afterglow extinction (green, KR11; brown PL13) have systematically more massive and dust extinguished sight lines than the optically selected hosts (blue, SG09). Outliers to this trend such as GRB 061222A or GRB 100621A have already been noted (e.g., Krühler et al. 2011, Perley et al. 2009), that were within blue, low-mass galaxies that were locally strongly extinguished along the line of sight. GRB 110918A is the first example of a dust-poor line of sight with a galaxy mass at the high-end of the distribution (i.e., \( \log_{10} \left( \frac{M_\star}{M_\odot} \right) > 10.5 \)). While in principle, cases like GRB 110918A would be easy to identify (bright afterglow, easy localization, bright host), no comparable example has been reported in the literature to date.

The host of GRB 110918A shows similar host-integrated extinction (\( A_V^{\text{GRB}} = 0.90 \) mag) to galaxies of a similar mass range (e.g., \( M_\star > 10^{10} M_\odot \) in Fig. 4 and \( M_\star > 4 \times 10^9 M_\odot \) in Fig. 15 of Perley et al. 2013) have an \( A_V^{\text{GRB}} \geq 1 \) mag). However, in comparison to the systems of similar mass, GRB 110918A exhibits at least 10 times less extinction along the GRB line of sight. Therefore, it is possible that: (i) the geometry of dust within the host of GRB110918A is more patchy than homogeneous in comparison to the rest of the massive GRB host population, in agreement with the example of GRB 100621A and 061222A, whereby clumpy dust was one explanation for having a highly extinguished afterglow within an unobscured galaxy (Krühler et al. 2011, Perley et al. 2013), or (ii) the progenitor had enough time to destroy local dust from its UV emission (see Perley et al. 2013 and references therein).

4.3. Fundamental Metallicity Relation

The difference between galaxies of long GRBs and that of normal star forming field galaxies is still an on going debate. We have derived estimates for the mass, metallicity and SFR of the host of GRB 110918A, which facilitates comparing this galaxy with respect to normal star forming galaxies through the fundamental metallicity relation (FMR; Mannucci et al. 2011). The plane of the FMR was derived from star forming SDSS galaxies in the mass range \( 9.2 < \log_{10} \left( \frac{M_\star}{M_\odot} \right) < 11.4 \) and is described by:

\[
12 + \log(O/H) = 8.90 + 0.47 \times (\mu_{0.32} - 10),
\]

where \( \mu_{0.32} = \log_{10} \left( \frac{M_\star}{M_\odot} \right) - 0.32 \times \log \left( \text{SFR} / M_\odot \text{yr}^{-1} \right) \). Using the SED-determined mass and the H\( \alpha \)-determined SFR, the metallicity from the FMR is \( 12 + \log(O/H) = 8.98 \pm 0.08 \), in agreement with the metallicity from the N II/H\( \alpha \) line ratio of \( 12 + \log(O/H) = 8.93 \pm 0.13 \). The method used in our metallicity estimate is the same as the one used by MN11 to construct the FMR, in order to ensure a direct comparison. The estimated errors are purely based on the uncertainties of the mass and SFR, and any systematic uncertainties from the method used to fit the stellar mass have been ignored.

The agreement in the characteristic properties of the host galaxy of GRB 110918A with the FMR (see Fig. 5) shows that the host galaxy has no deficit of metals in comparison to normal field galaxies, in line with the conclusions of SG09, MN11, KR11, and Michałowski et al. (2012). This illustrates that the mass and SFR of a GRB-selected galaxy, at least for this one event, can be used as a fair proxy for the metallicity even in the solar, or super-solar regime.
GRB hosts with supernovae hosts (Graham & Fruchter 2012),
A similar conclusion was reached based on a comparison of long
bursts, limiting the selection biases present in previous works.

Fig. 6: The metallicity determined from the fundamental metal-
licity relation (taken from MN11) vs. the parametric quantity
\( \mu_{0.32} \), plotted in grey for a range of star formation rates (SFR =
0 – 100 M\(_{\odot}\) yr\(^{-1}\)). Real quantities are plotted for MN11 (ma-
genta squares), GRB 080605 (Kruhler et al. 2012a cyan upward-
pointing triangle), and GRB 110918A (red). The host of GRB 110918A is well described by the SDSS determined FMR.

4.4. Metallicity and Long GRB Progenitors

Many authors have attributed the fact that most long GRB host
galaxies exhibit low metallicities as the result of an environmen-
tal preference, rather than the effect of the FMR (e.g., Modjaz
et al. 2008; Graham & Fruchter 2012; Perley et al. 2013).

This dependence on metallicity has also led to the prediction
that the lower the progenitor metallicity, the larger the angular
momentum, and thus the higher the energy output \( E_{\gamma,\text{iso}} \) of the
GRB (MacFadyen & Woosley 1999). Initial studies indeed
showed an anti-correlation between these two quantities (Stanek
et al. 2006), together with a cut-off metallicity above which long
GRBs (for \( z < 0.2 \)) are no longer created, i.e., \( Z < 0.15 Z_{\odot} \).

More recent studies, however, which include long GRBs at
cosmological redshifts and exclude sub-luminous GRBs (Wolf
& Podsiadlowski 2007; Levesque et al. 2010c) indicate that there
is no clear anti-correlation between metallicity and the
GRB’s energy output, as shown in Fig. 7. The prompt emis-
sion of GRB 110918A yielded an energy output of \( E_{\gamma,\text{iso}} =
1.9 \times 10^{54} \text{ erg} \) (Frederiks & Pal’shin 2011) within the top 2% of the
GRB population (Amati et al. 2008; Frederiks et al. 2013). This
makes GRB 110918A one of the most energetic long GRBs
yet observed and its host one of the most metal rich galaxies,
in contradiction to the idea of a correlation between \( E_{\gamma,\text{iso}} \) and
metallicity.

Recently, Perley et al. (2013) performed an extensive pho-
tometric study of host galaxies selected from a sample of dark
bursts, limiting the selection biases present in previous works.
However, while the inclusion of dark GRB hosts increases the
consistency of GRB hosts with the star formation weighted sam-
ple of field galaxies, there is still a clear lack of high-mass galax-
ies at \( z \leq 1.5 \). Associating the galaxy mass with metallicity, this
provides indirect evidence for a metallicity effect in GRB hosts.

A similar conclusion was reached based on comparison of long
GRB hosts with supernovae hosts (Graham & Fruchter 2012),
namely that long GRB hosts show a strong preference for lower
metallicity environments relative to other populations of star
forming galaxies, with a metallicity cut-off of \( Z < 0.5 Z_{\odot} \). This
cut-off is not consistent with the host galaxy of GRB 110918A,
even if metallicity dispersions of \( \sim 0.3 \) dex are considered (Niino
2011).

5. Conclusion

We observed the afterglow of GRB 110918A and its associated
host galaxy and obtained photometry and spectroscopy of both.
The extensive follow-up campaign has allowed us to measure the
afterglow sight-line extinction as well as the attenuation of the
galaxy’s stellar and gas-phase component. We further derive the
host’s integrated SFR, stellar mass and gas-phase metallicity. In
summary, this burst has revealed the following properties with
respect to the long GRB population:

1. The SED determined stellar mass of \( \log_{10}(M_*/M_{\odot}) =
10.68 \pm 0.16 \) makes the host of GRB 110918A one of the
most massive galaxies selected by a GRB at \( z \sim 1 \).

2. GRB 110918A is the first relatively unobscured afterglow
\( (A_V^{\text{GRB}} \sim 0.16 \text{ mag}) \) that has been detected in a very massive
host galaxy, suggesting that the geometry of dust is more
clumpy than homogeneous or local dust has been destroyed
by the progenitor.

3. The optical/NIR spectrum reveals a solar metallicity envi-
ronment (0.9 – 1.7 \( Z_{\odot} \), depending on the chosen diagnostic),
making it one of the most metal-rich long GRB host galaxies
found yet.

4. Using the fundamental metallicity relation and the measured
SFR, stellar mass and metallicity, we show that the host of
GRB 110918A is no different to star forming galaxies se-
lected through their own stellar light.

5. The large energy output from the \( \gamma \)-ray emission of GRB
110918A and the large metallicity content of the host galaxy,
is in strong contradiction with there being an anti-correlation
between energy output of the GRB and environmental metal-
licity.
Appendix A: The Afterglow Light Curve

The afterglow of GRB 110918A was imaged for over 40 days after the trigger with GROND in the $g', r', i', z'$, $JHK_S$ bands (outlined in Sect. 2.2). Utilising the deep observations of the host, the underlying contribution from the host galaxy was subtracted using the High Order Transform of PSF and Template Subtraction package, HOTPANTS\(^{11}\) v5.1.10b. The resulting afterglow light curve can be seen in Fig. A.1, the raw data can be found in Tables A.2 and A.3 and the host subtracted data can be found in Tables A.4 and A.5. The standard stars used in $g', r', i', z'$ for relative calibration can be found in Table A.1.

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Appendix B: The Afterglow’s Sight-Line Spectrum

The spectra obtained with GMOS and OSIRIS (see Sect. 2.6) reveal many absorption lines of gas along the line of sight toward the afterglow, specifically of the following species: Fe II (2344, 2374, 2382, 2586, 2600), Mg II (2803, 2796), Mg I (2853) and Ca II (3935, 3970). The equivalent widths of the metals are listed in Table B.1.

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Appendix C: The Host’s Emission Lines

Two spectra of the host galaxy were obtained with OSIRIS and X-shooter (see Sect. 3.3), showing the following emission lines: Hα and Hβ transitions from the Balmer series and also forbidden transitions of [O II] and [N II] (only [O II] emission was detected with OSIRIS, and so for consistency only the X-shooter emission lines are shown). All of the 2D spectral images and 1D Gaussian fits can be seen in Fig C.1.

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10

\(^{11}\) http://www.astro.washington.edu/users/becker/hotpants.html
All magnitudes have been corrected for Galactic foreground reddening. No correction has been made to subtract the flux contribution from the underlying host galaxy.

### Table A.1: Optical reference stars.

| R.A. (J2000) | Dec. (J2000) | g'   | r'   | i'   | z'   |
|--------------|-------------|------|------|------|------|
| 02:10:16.65  | -27:06:22.7 | 19.85 ± 0.03 | 19.64 ± 0.03 | 19.85 ± 0.04 | 19.74 ± 0.04 |
| 02:10:11.56  | -27:04:53.9 | 20.28 ± 0.03 | 19.86 ± 0.03 | 19.72 ± 0.04 | 19.72 ± 0.05 |
| 02:10:13.25  | -27:07:04.0 | 19.82 ± 0.03 | 19.48 ± 0.03 | 19.30 ± 0.03 | 19.27 ± 0.04 |
| 02:10:12.62  | -27:08:12.2 | 20.83 ± 0.04 | 19.37 ± 0.03 | 17.96 ± 0.03 | 17.27 ± 0.03 |

### Table A.2: GROND photometric data $g'r'i'z'$.

| $T_{	ext{med}} - T_0$ | Exposure | g'   | r'   | i'   | z'   |
|------------------------|----------|------|------|------|------|
| s                      | s        | magAB| magAB| magAB| magAB|
| 0                      | 193892   | 691  | 20.43 ± 0.04 | 20.15 ± 0.02 | 19.92 ± 0.04 | 19.80 ± 0.07 |
| 0                      | 194311   | 1526 | 20.39 ± 0.04 | 20.16 ± 0.03 | 19.93 ± 0.03 | 19.73 ± 0.08 |
| 0                      | 194724   | 699  | 20.42 ± 0.03 | 20.18 ± 0.02 | 19.92 ± 0.04 | 19.80 ± 0.06 |
| 0                      | 204203   | 683  | 20.48 ± 0.03 | 20.25 ± 0.02 | 20.05 ± 0.03 | 19.87 ± 0.06 |
| 0                      | 204615   | 1508 | 20.48 ± 0.03 | 20.25 ± 0.02 | 20.02 ± 0.03 | 19.84 ± 0.06 |
| 0                      | 205025   | 689  | 20.51 ± 0.03 | 20.28 ± 0.02 | 20.02 ± 0.03 | 19.89 ± 0.06 |
| 0                      | 214526   | 693  | 20.56 ± 0.03 | 20.33 ± 0.02 | 20.09 ± 0.04 | 19.98 ± 0.06 |
| 1                      | 215017   | 1674 | 20.56 ± 0.04 | 20.33 ± 0.02 | 20.11 ± 0.03 | 19.90 ± 0.07 |
| 1                      | 215504   | 700  | 20.56 ± 0.05 | 20.32 ± 0.03 | 20.12 ± 0.04 | 19.91 ± 0.07 |
| 1                      | 290361   | 691  | 21.09 ± 0.02 | 20.81 ± 0.02 | 20.66 ± 0.03 | 20.40 ± 0.06 |
| 1                      | 290775   | 1519 | 21.11 ± 0.03 | 20.88 ± 0.03 | 20.65 ± 0.04 | 20.44 ± 0.06 |
| 1                      | 291188   | 693  | 21.09 ± 0.03 | 20.83 ± 0.02 | 20.62 ± 0.03 | 20.44 ± 0.05 |
| 1                      | 381456   | 1727 | 21.68 ± 0.02 | 21.30 ± 0.02 | 21.06 ± 0.03 | 20.96 ± 0.05 |
| 1                      | 553350   | 1732 | 22.19 ± 0.04 | 21.96 ± 0.03 | 21.59 ± 0.06 | 21.30 ± 0.07 |
| 1                      | 725709   | 1727 | 22.62 ± 0.05 | 22.46 ± 0.05 | 22.02 ± 0.09 | 21.54 ± 0.10 |
| 1                      | 981853   | 3455 | 22.89 ± 0.06 | 22.76 ± 0.07 | 22.02 ± 0.09 | 21.60 ± 0.09 |
| 1                      | 1507300  | 5327 | 23.09 ± 0.07 | 22.84 ± 0.08 | 22.05 ± 0.07 | 21.75 ± 0.09 |

**Notes.** All magnitudes have been corrected for Galactic foreground reddening. No correction has been made to subtract the flux contribution from the underlying host galaxy.

### Table A.3: GROND photometric data $JHK_s$.

| $T_{	ext{med}} - T_0$ | Exposure | J    | H    | K    |
|------------------------|----------|------|------|------|
| s                      | s        | magAB| magAB| magAB|
| 0                      | 126393   | 82   | 18.93 ± 0.08 | 18.76 ± 0.08 |
| 0                      | 194337   | 1579 | 19.40 ± 0.09 | 19.18 ± 0.12 | 18.84 ± 0.15 |
| 0                      | 204643   | 1560 | 19.50 ± 0.08 | 19.19 ± 0.12 | 18.90 ± 0.16 |
| 0                      | 215045   | 1726 | 19.58 ± 0.10 | 19.35 ± 0.12 | 18.84 ± 0.15 |
| 0                      | 290803   | 1571 | 19.78 ± 0.09 | 19.64 ± 0.12 | 18.90 ± 0.16 |
| 0                      | 381482   | 1773 | 20.21 ± 0.10 | 19.73 ± 0.16 | 19.03 ± 0.16 |
| 0                      | 553375   | 1779 | 20.53 ± 0.14 | 20.17 ± 0.17 | 19.25 ± 0.19 |
| 0                      | 725734   | 1774 | 20.82 ± 0.16 | 20.43 ± 0.21 | 19.64 ± 0.19 |
| 0                      | 981879   | 3455 | 21.08 ± 0.15 | 20.59 ± 0.18 | 19.56 ± 0.28 |
| 0                      | 1507330  | 5379 | 20.77 ± 0.12 | 20.65 ± 0.16 | 19.50 ± 0.27 |

**Notes.** All magnitudes have been corrected for Galactic foreground reddening. No correction has been made to subtract the flux contribution from the underlying host galaxy.
Table A.4: GROND host subtracted photometric data $g'/r'/i'$.  

| $T_{\text{mid}} - T_0$ | Exposure | $g'$ | $r'$ | $i'$ | $z'$ |
|------------------------|----------|------|------|------|------|
| 193932                 | 691      | $20.48 \pm 0.04$ | $20.14 \pm 0.02$ | $19.93 \pm 0.02$ | $19.87 \pm 0.03$ |
| 194274                 | 699      | $20.52 \pm 0.03$ | $20.08 \pm 0.03$ | $19.93 \pm 0.03$ | $19.86 \pm 0.04$ |
| 204203                 | 683      | $20.46 \pm 0.04$ | $20.16 \pm 0.02$ | $20.02 \pm 0.02$ | $19.88 \pm 0.05$ |
| 205025                 | 689      | $20.51 \pm 0.04$ | $20.26 \pm 0.02$ | $20.03 \pm 0.03$ | $19.91 \pm 0.04$ |
| 214527                 | 693      | $20.65 \pm 0.03$ | $20.28 \pm 0.02$ | $20.13 \pm 0.03$ | $20.05 \pm 0.03$ |
| 215504                 | 700      | $20.63 \pm 0.04$ | $20.30 \pm 0.02$ | $20.18 \pm 0.03$ | $20.14 \pm 0.04$ |
| 290776                 | 1519     | $20.99 \pm 0.04$ | $20.70 \pm 0.03$ | $20.52 \pm 0.03$ | $20.43 \pm 0.04$ |
| 381457                 | 1727     | $21.67 \pm 0.03$ | $21.31 \pm 0.02$ | $21.14 \pm 0.03$ | $21.05 \pm 0.04$ |
| 553350                 | 1732     | $22.43 \pm 0.04$ | $22.04 \pm 0.03$ | $21.89 \pm 0.04$ | $21.75 \pm 0.05$ |
| 725709                 | 1727     | $23.09 \pm 0.05$ | $22.65 \pm 0.04$ | $22.53 \pm 0.06$ | $22.51 \pm 0.06$ |
| 981853                 | 3455     | $23.78 \pm 0.06$ | $23.30 \pm 0.06$ | $23.31 \pm 0.10$ | $23.03 \pm 0.28$ |
| 1507300                | 5327     | $> 24.80$ | $> 24.15$ | $> 22.84$ | $> 22.01$ |

Notes. All magnitudes have been corrected for Galactic foreground reddening.

Table A.5: GROND host subtracted photometric data $JHK_s$.  

| $T_{\text{mid}} - T_0$ | Exposure | $J$ | $H$ | $K_s$ |
|------------------------|----------|-----|-----|------|
| s s mag$_{AB}$ | mag$_{AB}$ | mag$_{AB}$ |
| 126444                 | 393      | $18.74 \pm 0.05$ | $18.47 \pm 0.07$ | .... |
| 193921                 | 745      | $19.42 \pm 0.06$ | $19.04 \pm 0.05$ | .... |
| 194338                 | 790      | .... | .... | $18.92 \pm 0.08$ |
| 194751                 | 752      | $19.54 \pm 0.06$ | $19.25 \pm 0.06$ | .... |
| 204231                 | 736      | $19.35 \pm 0.06$ | $19.39 \pm 0.06$ | .... |
| 204643                 | 780      | .... | .... | $19.05 \pm 0.07$ |
| 205052                 | 742      | $19.48 \pm 0.06$ | $19.29 \pm 0.06$ | .... |
| 214555                 | 746      | $19.59 \pm 0.06$ | $19.45 \pm 0.08$ | .... |
| 215045                 | 863      | .... | .... | $19.17 \pm 0.07$ |
| 215531                 | 753      | $19.49 \pm 0.06$ | $19.30 \pm 0.06$ | .... |
| 290803                 | 1571     | $20.12 \pm 0.08$ | $19.80 \pm 0.07$ | $> 18.93$ |
| 381482                 | 1773     | $20.67 \pm 0.10$ | $20.22 \pm 0.08$ | $> 19.34$ |
| 553375                 | 1799     | $> 20.48$ | $> 20.91$ | $> 18.44$ |
| 725734                 | 1774     | $> 20.71$ | $> 20.55$ | $> 18.91$ |
| 981879                 | 3455     | $> 20.80$ | $> 20.80$ | $> 18.44$ |
| 1507329                | 5379     | $> 20.77$ | $> 20.49$ | $> 19.09$ |

Notes. All magnitudes have been corrected for Galactic foreground reddening.

Table B.1: Equivalent widths measured for the absorption lines of the afterglow.

| $\lambda_{\text{obs}}$ | Feature | Contaminants | EW$_{\text{obs}}$ | EW$_{\text{rest}}$ | $z$ |
|------------------------|---------|--------------|-------------------|-------------------|----|
| 4650.1 & 4650.2 Fe II2444.2 & Fe II'2345.0 | $4.3 \pm 0.4$ | $2.2 \pm 0.2$ | 0.9838 |
| 4713.4 Fe II2374.5 & Fe II'2345.1 | $4.3 \pm 0.4$ | $2.2 \pm 0.2$ | 0.9838 |
| 4720.5 Fe II2382.8 & Fe II'2345.1 | $8.4 \pm 0.6$ | $4.2 \pm 0.3$ | 0.9838 |
| 5132.7 Fe II2586.7 & Mn II2594.5 | $3.7 \pm 0.4$ | $1.9 \pm 0.2$ | 0.9838 |
| 5157.7 Fe II2600.2 & Mn II2594.5, Fe II'2586.7 | $6.3 \pm 0.5$ | $3.2 \pm 0.2$ | 0.9838 |
| 5547.3 Mn II2796.4 & Mn II2600.2 | $11.9 \pm 0.4$ | $6.0 \pm 0.2$ | 0.9838 |
| 5560.1 Mg II2803.5 & Fe II2600.2 | $11.9 \pm 0.4$ | $6.0 \pm 0.2$ | 0.9838 |
| 5660.2 Mg II2530.0 & Fe II2600.2 | $4.3 \pm 0.4$ | $2.2 \pm 0.2$ | 0.9838 |
| 7806.1 & 7806.2 Ca II3969.4 & Ca II3934.8 & Ca II3969.6 | $4.3 \pm 0.4$ | $2.2 \pm 0.2$ | 0.9838 |

Notes. The redshift was determined for those lines with no contaminants. (1) Blended lines.
Fig. C.1: The 2D spectra of the host of GRB 110918A, depicting four different emissions ([N II], [O II], Hα, Hβ). Overplotted is our Gaussian fit where areas that overlay telluric lines are shown in white and excluded from the fit. All the values presented are raw values and do not include slit-loss or extinction corrections. Each image has been smoothed in both pixel directions for presentation purposes. (a): The Balmer series transition Hα. (b): The Balmer series transition Hβ. (c): The forbidden transition [N II]. (d): The forbidden transition [O II].