

# The host galaxy of GRB 031203: a new spectroscopic study

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## ABSTRACT

**Aims.** The host galaxy of the long-duration gamma-ray burst (GRB) 031203 (HG 031203) offers a precious opportunity to study in detail the environment of a nearby GRB. The aim is to better characterize this galaxy and analyse the possible evolution with time of the spectroscopic quantities we derive.

**Methods.** We analyse HG 031203 using a set of optical spectra acquired with the ESO-VLT and Keck telescope. We compare the metallicity, luminosity and star formation properties of this galaxy and of the other supernova-long gamma-ray burst hosts in the local universe ( $z < 0.2$ ) against the KPNO International Spectroscopic Survey.

**Results.** HG 031203 is a metal poor, actively star forming galaxy (star formation rate of  $12.9 \pm 2.2 M_{\odot} \text{ yr}^{-1}$ ) at  $z = 0.1054$ . From the emission-line analysis we derive an intrinsic reddening  $E_{\text{HG}}(B - V) \approx 0.4$ . This parameter doesn't show a compelling evidence of evolution at a month time-scale. We find an interstellar medium temperature of  $\approx 12\,500$  K and an electronic density of  $N_e = 160 \text{ cm}^{-3}$ . After investigating for possible Wolf-Rayet emission features in our spectra, we consider dubious the classification of HG 031203 as a Wolf-Rayet galaxy. Long gamma-ray burst (LGRB) and supernova hosts in the local universe ( $z < 0.2$ ) show, on average, specific star formation rates higher than ordinary star forming galaxy at the same redshift. On the other hand, we find that half of the hosts follows the metallicity–luminosity relation found for star-burst galaxies; HG 031203 is a clear outlier, with its really low metallicity ( $12 + \log(\text{O}/\text{H}) = 8.12 \pm 0.04$ ).

**Key words.** gamma rays: bursts – galaxies: individual: GRB 031203 – ISM: abundances – stars: Wolf-Rayet

## 1. Introduction

While it is now widely believed that long gamma-ray bursts (LGRBs) arise from the core collapse of young massive stars (“collapsar” model, Woosley 1993; MacFadyen & Woosley 1999), the nature of their host galaxies (HGs) is still under discussion. The properties of about 50 HGs of LGRBs have been identified to date: nevertheless, we cannot tell whether they form a new class of objects or just a sub-sample of an already known population of galaxies.

Among the physical properties of the circumburst environment, the metallicity seems to play a central role in the formation of these highly energetic events. The “collapsar” model favours progenitors of low metallicity because of the reduced angular momentum loss and mass loss via strong winds at the surface of the star. Limited chemical evolution of GRB hosts is also the explanation suggested by Fruchter et al. (2006) in order to account for the observed differences between LGRB HGs and HGs of core-collapse supernovae (CC SNe): while the rate of CC SNe (per unit stellar luminosity) is almost equal in spiral and irregular galaxies (Cappellaro et al. 1999; Leaman et al. 2007), the overwhelming majority of LGRBs occur in faint, small irregulars. Moreover, CC SN positions follow the blue light of their host galaxies within statistical uncertainties, while LGRBs are far more concentrated on the brightest HG regions

(Fruchter et al. 2006). From the perspective of obtaining an accurate census of star formation in the universe, the preference of LGRBs for low-metallicity galaxies is a potential bias that limits the use of their hosts as cosmological tracers, at least at low redshift. However, spectroscopic measurements of the host metallicity in the redshift interval  $0.4 < z < 1$  indicate that these objects follow the mass-metallicity relation recently found (Savaglio et al. 2005) for star-forming galaxies in the same redshift interval (Savaglio et al. 2006). In this paper, we present a case study of the GRB host population: the host galaxy of the long-duration ( $\sim 30$  s) GRB 031203 that triggered the IBIS instrument of INTEGRAL (Götz et al. 2003; Sazonov et al. 2004) on 2003 December 3.91769 (UT dates are used throughout this paper). A small galaxy was found spatially coincident with the X-ray source (Hsia et al. 2003) and was later identified as the GRB host. From optical spectroscopy, Prochaska et al. (2004) derived for HG 031203 a redshift  $z = 0.1055$ .

While making GRB 031203 one of the closest GRBs ever observed, the proximity of the burst also triggered particular interest in attempting to detect an associated SN explosion. The host was therefore monitored independently by different groups, searching for an SN rebrightening (Thomsen et al. 2004; Cobb et al. 2004; Gal-Yam et al. 2004). The light curve of HG 031203 indeed showed the typical photometric variability of an SN

superimposed on a host galaxy. Ultimate confirmation came from the spectroscopic observations of Tagliaferri et al. (2004); the event was named SN 2003lw. We refer to Malesani et al. (2004) for a complete discussion of the SN 2003lw explosion and for details about HG 031203 photometry.

The proximity of HG 031203 allows us to perform a detailed analysis of its physical properties. From high-quality optical observations, we determine the host-galaxy metallicity, intrinsic reddening, nebular parameters, SFR, and specific star-formation rate (SSFR). Given the present set of data we can test the potential evolution of the host galaxy parameters on a month time scale. We further characterize this object, directly contrasting its physical properties with the KPNO International Spectroscopic Survey (KISS), an emission-line survey of galaxies in the local universe ( $z \leq 0.1$ ) that utilized low-dispersion objective-prism spectra (Salzer et al. 2000).

In order to better understand the nature of galaxies that are able to produce one of the most energetic events in the universe, we consider the largest sample of local LGRB hosts with associated SN explosions. This sample includes HG 980425 ( $z = 0.0085$ ; Galama et al. 1998), HG 030329 ( $z = 0.1685$ ; Sollerman et al. 2005; Gorosabel et al. 2005; Thöne et al. 2006), HG 031203 ( $z = 0.10536$ , this work), and HG 060218 ( $z = 0.0335$ ; Modjaz et al. 2006; Wiersema et al. 2007). We focus on the metallicity and star-formation properties of these galaxies, with the aim of shedding light on the possible peculiarity of these objects.

This paper is organised as follows. Section 2 reviews the observations and shortly describes the performed data reduction. We assess the intrinsic and Galactic extinction toward GRB 031203 in Sect. 3, where the host is characterized in terms of emission-line fluxes. We perform an emission-line analysis to determine the host relative chemical abundances and star-formation properties in Sects. 4 and 5, respectively. Section 7 analyses the continuum emission of HG 031203, while in Sect. 6 we carefully investigate the possible presence of Wolf-Rayet (WR) features in the spectra of HG 031203. Our findings are discussed and summarized in Sect. 8. Finally, conclusions are drawn in Sect. 9.

Throughout this paper standard  $\Lambda$  cosmology is used:  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_\Lambda = 0.7$ ,  $\Omega_m = 0.3$ .

## 2. Observations and data analysis

**Photometry.** We acquired  $U$ ,  $B$ , and  $V$  photometry of HG 031203 with VLT+FOR2 during the night of 2004 March 26th (that is, about 4 months after the GRB). We expect negligible contribution from SN 2003lw at this epoch (see, e.g., Mazzali et al. 2006). Observing conditions were photometric. Data reduction was performed following standard procedures. Flux calibration was achieved by observing the Landolt (1992) standard field Rubin 152. The photometric calibration was carried out including appropriate color terms, resulting in a systematic uncertainty of  $\sim 0.05$  mag. The host galaxy was clearly detected in all filters, and its magnitudes are reported in Table 2. For the extinction correction we used a Galactic color excess  $E_{\text{MW}}(B - V) = 0.72$  and an intrinsic reddening  $E_{\text{HG}}(B - V) = 0.38$ , value measured from the spectrum taken on March 2nd, about 20 days before the photometric observations (see Sect. 3).  $K$ -corrections were derived interpolating the extinction corrected fluxes at the required wavelengths. In particular we assessed the  $I$ -band  $K$ -correction considering the spectral slope of the spectrum taken on March 2nd.

**Table 1.** Observing log (photometry). Middle exposures dates are provided.

Date (UT)	Band	Exp. (s)	Seeing (")	Instrument
2004 Mar. 27.1044	$V$	$2 \times 120$	1.1	VLT+FOR2
2004 Mar. 27.0958	$B$	$2 \times 300$	0.9	VLT+FOR2
2004 Mar. 27.0835	$U$	$3 \times 300$	1.1	VLT+FOR2

**Table 2.** Observed magnitudes and extinction and  $K$ -corrected absolute magnitudes of HG 031203. The errors reported account for uncertainties coming from the flux calibration procedure and the intrinsic extinction correction.

Band	Obs. mag. (mag)	Abs. mag. (mag)
$U$	22.31 $\pm 0.18$	-21.38 $\pm 0.47$
$B$	22.32 $\pm 0.05$	-21.00 $\pm 0.39$
$V$	20.53 $\pm 0.05$	-21.02 $\pm 0.31$
$R^a$	20.44 $\pm 0.02$	-20.54 $\pm 0.24$
$I^a$	19.40 $\pm 0.04$	-19.90 $\pm 0.16$

<sup>a</sup> From Mazzali et al. (2006).

From the badly constrained Galactic color excess (see Sect. 3) we derive additional systematic errors of 0.32, 0.22, 0.20, 0.15 and 0.10 mag for the  $U B V R$  and  $I$ -band extinction corrected absolute magnitudes respectively.

**Spectroscopy.** We acquired optical spectra of the host galaxy of GRB 031203 with the European Southern Observatory Very Large Telescope (ESO-VLT, Cerro Paranal, Chile) and the Keck-I telescope (Hawaii, USA).

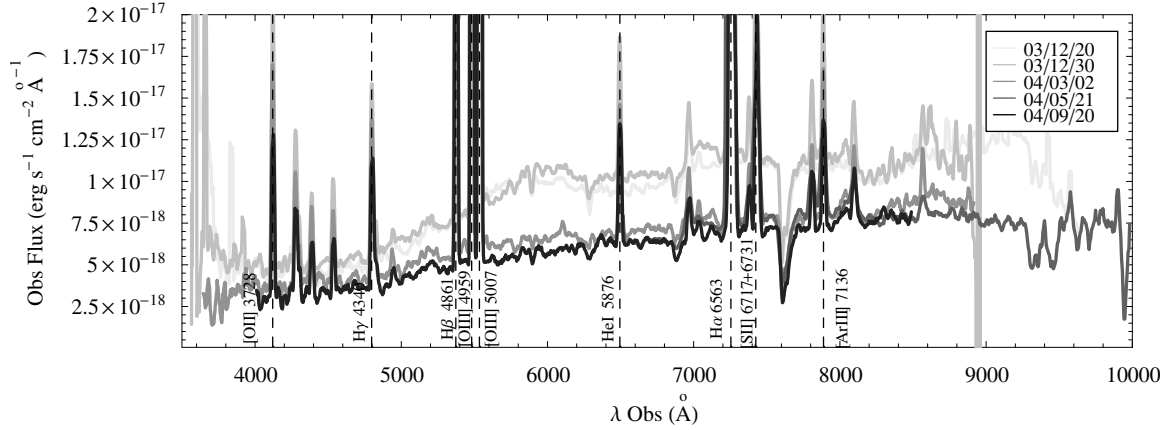
We first observed HG 031203 on 2003 December 20.29 using the FOR2 (focal reducer/low-resolution spectrograph) instrument on VLT-UT4 (Yepun), characterized by a spatial resolution of  $0.126'' \text{ pix}^{-1}$ . With the 300V grism, the inverse dispersion was  $112 \text{ \AA mm}^{-1}$  ( $1.68 \text{ \AA pix}^{-1}$ ), while we covered the wavelength range  $3300\text{--}8700 \text{ \AA}$ . Owing to the excellent seeing on that night ( $0.5''$ ), the two brightest emission lines ( $H\alpha$  and  $[\text{O III}] \lambda 5007$ ) are slightly saturated.

In order to extend the spectral coverage up to  $11\,000 \text{ \AA}$ , we also acquired spectra using the 150I grism along with the order-blocking filter OG590. The inverse dispersion was  $3.45 \text{ \AA pix}^{-1}$  ( $230 \text{ \AA mm}^{-1}$ ). After calibration, we compared the fluxes in the wavelength region common to the two grisms (300V and 150I) and found good agreement. All our observations were split into shorter exposures (see Table 3), and Fig. 1 shows for each night the co-added spectrum.

Our second run was performed on 2003 December 30.22 using the FOR1 on VLT-UT1 (Antu). This instrument is characterized by a lower spatial resolution ( $0.2'' \text{ pix}^{-1}$ ). The inverse dispersion is worse, too:  $2.64 \text{ \AA pix}^{-1}$  and  $5.5 \text{ \AA pix}^{-1}$  for the 300V and 150I grisms, respectively. During that night the seeing was  $0.6''$ ; no emission lines were saturated.

We acquired a first reference host-galaxy spectrum on 2004 March 02.09; at that time we expected SN 2003lw to have largely faded away, leaving a negligible contribution to the total flux. This spectrum was acquired with FOR1 + grism 300V, and it allowed us to evaluate the supernova contribution in earlier spectra.

On 2004 March 16th, HG 031203 was observed with the 10 m Keck-I telescope. Spectra were acquired using the low resolution imaging spectrometer (LRIS; Oke et al. 1995) and the



**Fig. 1.** VLT spectra of the host galaxy of GRB 031203. The different continuum emission is due to the contribution of SN2003lw. Note the strong H $\alpha$  emission, corresponding to a SFR  $\approx 13 M_{\odot} \text{ yr}^{-1}$ . No extinction correction has been applied.

**Table 3.** Observing log (spectroscopy). Middle exposures dates are provided.

Date (UT)	Grism	Exp. (s)	Seeing (")	Instrument
2003 Dec. 20.29	150I	900	0.5	VLT+FORS2
2003 Dec. 20.30	150I	900	0.5	VLT+FORS2
2003 Dec. 20.33	300V	2700	0.5	VLT+FORS2
2003 Dec. 20.36	300V	2700	0.5	VLT+FORS2
2003 Dec. 30.22	150I	900	0.5	VLT+FORS1
2003 Dec. 30.23	150I	900	0.5	VLT+FORS1
2003 Dec. 30.28	300V	2700	0.5	VLT+FORS1
2003 Dec. 30.32	300V	2700	0.5	VLT+FORS1
2004 Mar. 02.09	300V	1800	0.6	VLT+FORS1
2004 Mar. 02.11	300V	1800	0.6	VLT+FORS1
2004 Mar. 02.13	300V	1800	0.6	VLT+FORS1
2004 Mar. 02.16	300V	1800	0.6	VLT+FORS1
2004 Mar. 16.33	400 I <sup>a</sup>	1200	2.3	Keck+LRIS+D560
2004 Mar. 16.35	600 B <sup>a</sup>	1200	2.3	Keck+LRIS+D560
2004 May. 21.98	150I	900	0.6	VLT+FORS1
2004 May. 21.99	150I	900	0.6	VLT+FORS1
2004 May. 22.01	150I	900	0.6	VLT+FORS1
2004 Sep. 20.35	300V	1800	0.6	VLT+FORS2
2004 Sep. 20.37	300V	1800	0.6	VLT+FORS2

<sup>a</sup> Grating.

D560 dichroic. Unfortunately, the night was characterized by poor seeing conditions (about 2.3").

Additional reference 150I spectra were obtained on 2004 May 21 with the FORS1 instrument on VLT-UT1. This observation confirmed that the SN contribution was negligible in March ( $\sim 0.03$  mag).

Our last HG 031203 spectra date back to more than 9 months after the trigger of the burst: on 2004 September 20, we observed the host galaxy with FORS2, grism 300V on VLT-UT4. The seeing was very good (0.6"), though no emission lines show saturation.

Each of the VLT spectra of HG 031203 was obtained using a long slit 1" wide, but the slit used for the standard stars LTT3864 and LTT1788 was 5" wide. Keck spectra were instead acquired using a 1.5" slit. All nights of observation were photometric. The complete observing log is given in Table 3.

Data were reduced following standard procedures. After correcting for atmospheric extinction and telluric bands, we calibrated the observed fluxes using spectrophotometric standards taken during the same night. Keck fluxes were normalized to

VLT observations. For the VLT spectra, we evaluate a relative flux uncertainty of  $\sim 2\%$  in the wavelength range 4100–7150 Å from the calibration of the spectrophotometric standards. The uncertainty increases considerably outside this range of wavelengths, reaching  $\sim 16\%$  shortward of 4000 Å. For this reason, we do not consider this region of VLT spectra in the following analysis. For the Keck spectra a relative flux uncertainty of  $\sim 5\%$  is expected.

The entire analysis of the reduced spectra was carried out without any standard package, in order to have more flexibility and control in the adopted procedures. For the first night of observation we analyse each segment and then we focus on the co-added spectrum. For the following nights, we compare the co-added spectrum to the one acquired on December 20: in this way we are able to detect any variability and spurious faint lines. We find that all of the identified lines are narrower than the instrument resolution; hence we decided to fit a Gaussian of constant width to each emission line profile. Using the four strongest emission features of each spectrum we derive a redshift  $z = 0.10536 \pm 0.00007$ . We believe our uncertainty to be dominated by systematics, since line profiles are not strictly Gaussian. Prochaska et al. (2004) found  $z = 0.1055 \pm 0.0001$ . The host galaxy of GRB 031203 therefore belongs to the local universe: with a luminosity distance  $D_L = 473$  Mpc, GRB 031203 is one of closest known long-duration bursts, along with the anomalous GRB 980425 (Galama et al. 1998), GRB 030329 and GRB 060218.

Our measures are summarized in Tables 4 and 5. We list observed fluxes, extinction-corrected fluxes, and equivalent widths of emission lines with certain detection and identification. Observed-flux uncertainties are dominated by errors in the flux-calibration procedure and in the subtraction of the underlying continuum. For extinction-corrected flux uncertainties, we also consider errors coming from the extinction-correction procedure (see Sect. 3).

### 3. Galactic and intrinsic extinction

The aim of this section is to estimate the extinction correction necessary for calculating the total line fluxes of the observed emission lines. First, we try to estimate the Milky Way absorption; second, we derive the host-galaxy extinction correction using Balmer decrements.

The Galactic extinction correction is not easy to assess because of the location of GRB 031203: the burst is very close to

**Table 4.** Emission line summary (VLT observations).

$\lambda_{\text{rest}}$ (Å)	Ion	2003 December 20th				2003 December 30th			
		$EW_{\text{rest}}$ (Å)	Obs. flux ( $10^{-17}$ cgs)	Ext. corr. flux ( $10^{-17}$ cgs)		$EW_{\text{rest}}$ (Å)	Obs. flux ( $10^{-17}$ cgs)	Ext. corr. flux ( $10^{-17}$ cgs)	
3728.8	[OII]	52.04	26.65 ± 0.75	2718.66 ± 543.92	61.74	34.23 ± 2.49	2843.19 ± 571.69		
3868.7	[NeIII]	32.23	16.06 ± 0.45	1407.65 ± 275.24	32.01	17.69 ± 1.29	1269.62 ± 250.16		
3888.9	HeI	12.31	6.11 ± 0.17	523.63 ± 102.01	10.99	6.07 ± 0.44	426.31 ± 83.73		
3967.5	[NeIII]	18.01	8.80 ± 0.25	688.15 ± 132.05	16.92	9.32 ± 0.68	599.77 ± 116.24		
4101.7	HI	14.44	8.19 ± 0.23	547.38 ± 102.03	18.83	10.76 ± 0.78	595.35 ± 112.49		
4340.4	HI	35.02	19.58 ± 0.55	989.67 ± 173.78	36.77	22.48 ± 1.64	950.82 ± 170.61		
4363.2	[OIII]	6.05	3.45 ± 0.10	170.01 ± 29.67	6.74	4.18 ± 0.30	172.51 ± 30.79		
4471.5	HeI	3.43	2.20 ± 0.06	96.04 ± 16.28	2.74	1.90 ± 0.14	69.87 ± 12.16		
4861.3	HI	83.15	71.70 ± 2.03	2142.39 ± 326.70	95.63	83.45 ± 6.08	2135.91 ± 340.46		
4959.0	[OIII]	184.51	171.58 ± 4.85	4724.45 ± 702.59	210.11	192.84 ± 14.04	4566.96 ± 713.23		
5006.9	[OIII]	561.02	526.73 ± 14.90	13958.94 ± 2051.15	634.64	596.61 ± 43.43	13623.87 ± 2107.08		
5875.6	HeI	15.44	15.98 ± 0.45	244.34 ± 29.99	16.58	18.52 ± 1.35	250.52 ± 33.68		
6300.3	[OI]	4.09	4.72 ± 0.13	57.58 ± 6.57	4.48	5.57 ± 0.41	60.72 ± 7.74		
6312.1	[SIII]	2.77	3.21 ± 0.09	38.91 ± 4.43	2.28	2.88 ± 0.21	31.21 ± 3.97		
6363.8	[OI]	1.87	2.21 ± 0.06	26.14 ± 2.95	...	...	...		
6548.1	[NII]	9.62	11.88 ± 0.43	127.43 ± 14.21	7.38	9.51 ± 0.82	91.67 ± 12.08		
6562.9	HI	459.85	569.15 ± 20.52	6060.99 ± 674.36	484.55	621.59 ± 53.47	5944.68 ± 782.40		
6583.4	[NII]	25.18	31.24 ± 1.13	329.19 ± 36.50	26.45	33.79 ± 2.91	319.86 ± 42.01		
6678.2	HeI	6.58	6.47 ± 0.18	64.90 ± 6.93	4.16	7.94 ± 0.58	71.70 ± 8.72		
6716.5	[SII]	15.40	19.00 ± 0.54	186.82 ± 19.81	18.58	23.27 ± 1.69	206.04 ± 24.94		
6730.7	[SII]	12.43	15.28 ± 0.43	149.10 ± 15.77	14.19	17.74 ± 1.29	155.99 ± 18.85		
7065.3	HeI	6.81	8.13 ± 0.23	66.76 ± 6.63	8.42	10.51 ± 0.77	78.32 ± 9.07		
7135.8	[AIII]	15.36	18.50 ± 0.52	146.66 ± 14.37	15.49	19.49 ± 1.42	140.37 ± 16.12		
7281.3	HeI	1.34	1.56 ± 0.04	11.53 ± 1.10	...	...	...		
7319.9	[OII]	4.09	4.64 ± 0.13	33.56 ± 3.17	5.82	6.97 ± 0.51	45.95 ± 5.15		
7330.2	[OII]	3.93	4.43 ± 0.13	31.86 ± 3.00	2.89	3.44 ± 0.25	22.54 ± 2.52		
7751.0	[AIII]	4.38	5.51 ± 0.16	32.64 ± 2.82	3.52	4.65 ± 0.34	25.33 ± 2.69		
$\lambda_{\text{rest}}$ (Å)	Ion	2004 March 2nd				2004 September 20th			
		$EW_{\text{rest}}$ (Å)	Obs. flux ( $10^{-17}$ cgs)	Ext. corr. flux ( $10^{-17}$ cgs)		$EW_{\text{rest}}$ (Å)	Obs. flux ( $10^{-17}$ cgs)	Ext. corr. flux ( $10^{-17}$ cgs)	
3728.8	[OII]	70.77	28.41 ± 2.85	2325.44 ± 885.80	72.33	23.85 ± 1.22	2157.33 ± 373.52		
3868.7	[NeIII]	33.49	14.20 ± 1.43	1004.50 ± 374.40	40.04	13.76 ± 0.70	1072.90 ± 181.84		
3888.9	HeI	11.71	5.00 ± 0.50	346.29 ± 128.63	14.08	4.87 ± 0.25	371.16 ± 62.69		
3967.5	[NeIII]	21.83	9.60 ± 0.97	608.75 ± 222.90	22.36	7.90 ± 0.40	551.02 ± 91.78		
4101.7	HI	21.38	9.06 ± 0.91	494.01 ± 175.99	22.00	8.43 ± 0.43	504.45 ± 81.79		
4340.4	HI	42.53	20.09 ± 2.02	838.25 ± 282.35	47.28	19.33 ± 0.99	879.95 ± 135.07		
4363.2	[OIII]	7.40	3.53 ± 0.35	143.71 ± 48.13	8.05	3.31 ± 0.17	146.98 ± 22.44		
4471.5	HeI	...	...	...	...	...	...		
4861.3	HI	117.02	76.39 ± 7.68	1932.24 ± 571.15	129.95	71.46 ± 3.64	1949.33 ± 263.49		
4959.0	[OIII]	260.63	179.06 ± 18.00	4192.25 ± 1211.10	278.66	165.38 ± 8.43	4167.29 ± 550.92		
5006.9	[OIII]	784.34	551.31 ± 55.41	12448.40 ± 3557.12	870.54	513.48 ± 26.18	12467.11 ± 1630.82		
5875.6	HeI	22.18	16.67 ± 1.68	223.34 ± 54.33	26.79	18.97 ± 0.97	270.05 ± 30.26		
6300.3	[OI]	6.27	5.26 ± 0.53	56.86 ± 12.98	6.46	4.87 ± 0.25	55.65 ± 5.87		
6312.1	[SIII]	3.31	2.78 ± 0.28	29.89 ± 6.81	1.55	1.18 ± 0.06	13.43 ± 1.41		
6363.8	[OI]	2.53	2.18 ± 0.22	22.85 ± 5.17	...	...	...		
6548.1	[NII]	9.77	8.51 ± 1.04	81.40 ± 18.78	12.77	9.73 ± 0.52	98.07 ± 10.13		
6562.9	HI	655.58	569.14 ± 69.47	5396.04 ± 1242.59	757.17	577.85 ± 31.12	5776.77 ± 595.67		
6583.4	[NII]	33.30	28.75 ± 3.51	269.81 ± 61.96	37.45	28.62 ± 1.54	283.15 ± 29.11		
6678.2	[HeI]	8.58	7.19 ± 0.72	64.36 ± 13.89	8.81	6.77 ± 0.35	63.84 ± 6.38		
6716.5	[SII]	25.39	21.03 ± 2.11	184.68 ± 39.63	27.47	21.16 ± 1.08	195.65 ± 19.46		
6730.7	[SII]	20.73	17.11 ± 1.72	149.16 ± 31.94	22.23	17.14 ± 0.87	157.31 ± 15.61		
7065.3	HeI	10.52	9.16 ± 0.92	67.73 ± 13.77	10.82	8.57 ± 0.44	66.48 ± 6.28		
7135.8	[AIII]	21.71	18.95 ± 1.90	135.43 ± 27.22	20.70	16.60 ± 0.85	124.37 ± 11.63		
7281.3	HeI	...	...	...	...	...	...		
7319.9	[OII]	6.06	5.46 ± 0.55	35.75 ± 6.97	6.05	5.08 ± 0.26	34.77 ± 3.16		
7330.2	[OII]	5.03	4.45 ± 0.45	29.01 ± 5.65	4.58	3.83 ± 0.20	26.10 ± 2.37		
7751.0	[AIII]	5.24	5.33 ± 0.54	28.86 ± 5.24	...	...	...		

the Galactic plane, at  $l = 255^\circ$ ,  $b = -4.6^\circ$  (see Cobb et al. 2004 for detailed astrometry of HG 031203). According to the far-IR map by Schlegel et al. (1998), the sight line to HG 031203 has an inferred reddening value  $E_{\text{MW}}(B - V) = 1.04$ . However, Dutra et al. (2003) argue that the far-IR analysis overestimates the real

$E_{\text{MW}}(B - V)$  value by a factor of  $\sim 25\%$ . Consequently, they suggest scaling the previous value by that factor. Applying this correction, we get  $E_{\text{MW}}(B - V) = 0.78$ . However, the possibility of systematic errors in the Schlegel et al. (1998) analysis, errors which could lead to an underestimate of the reddening, has been

**Table 5.** Emission line summary (Keck observations).

$\lambda_{\text{rest}}$ (Å)	Ion	2004 March 16th				
		$EW_{\text{rest}}$ (Å)	Obs. flux ( $10^{-17}$ cgs)		Ext. corr. flux ( $10^{-17}$ cgs)	
3728.8	[OII]	46.52	27.78	$\pm 7.84$	2307.33	$\pm 1370.92$
3868.7	[NeIII]	26.97	14.10	$\pm 1.44$	1012.15	$\pm 527.31$
3888.9	HeI	10.00	5.18	$\pm 0.52$	364.01	$\pm 188.85$
3967.5	[NeIII]	16.27	8.59	$\pm 0.83$	552.53	$\pm 281.95$
4101.7	HI	19.05	10.20	$\pm 0.96$	564.08	$\pm 279.47$
4340.4	HI	33.87	16.92	$\pm 1.77$	715.57	$\pm 335.85$
4363.2	[OIII]	7.63	3.78	$\pm 0.40$	155.76	$\pm 72.73$
4471.5	HeI	...	...	...	...	...
4861.3	HI	94.18	76.15	$\pm 9.13$	1948.15	$\pm 805.41$
4959.0	[OIII]	202.60	160.19	$\pm 18.63$	3790.43	$\pm 1526.28$
5006.9	[OIII]	714.05	547.79	$\pm 62.78$	12497.30	$\pm 4969.05$
5875.6	HeI	18.89	15.34	$\pm 1.44$	207.30	$\pm 68.20$
6300.3	[OI]	7.61	6.12	$\pm 0.56$	66.62	$\pm 20.36$
6312.1	[SIII]	3.79	3.08	$\pm 0.28$	33.36	$\pm 10.17$
6363.8	[OI]	...	...	$\pm \dots$	...	...
6548.1	[NII]	11.31	8.99	$\pm 0.82$	86.50	$\pm 25.38$
6562.9	HI	719.14	574.08	$\pm 52.61$	5482.76	$\pm 1604.51$
6583.4	[NII]	39.40	31.64	$\pm 2.90$	299.19	$\pm 87.26$
6678.2	HeI	6.17	5.09	$\pm 0.47$	45.92	$\pm 13.19$
6716.5	[SII]	25.94	21.66	$\pm 2.01$	191.60	$\pm 54.68$
6730.7	[SII]	19.80	16.60	$\pm 1.54$	145.80	$\pm 41.51$
7065.3	HeI	...	...	...	...	...
7135.8	[AIII]	16.76	15.81	$\pm 1.56$	113.71	$\pm 30.31$

considered by Willick (1999). Moreover, Schlegel et al. (1998) invite the reader not to trust their predicted reddenings of sight lines at low Galactic latitudes ( $|b| < 5^\circ$ ) because of the unresolved temperature structure of our Galaxy and the presence of unremoved contaminating sources in their map. The sight line to HG 031203 falls in this category. Because of this, we need other independent estimates of the Galactic absorption.

First, Dutra et al. (2003) find a spectroscopic reddening  $E_{\text{MW}}(B - V) = 0.65$  for ESO 314-2. With a Galactic longitude  $l = 261.5^\circ$  and latitude  $b = 4.1^\circ$ , this galaxy is nearly symmetric to HG 031203 with respect to the Galactic plane. Since we do not expect the interstellar medium (ISM) to be highly clumped and irregularly distributed at this longitude, it seems reasonable to assume that the two objects are affected by a similar Galactic extinction. The mean reddening value found so far is then  $E_{\text{MW}}(B - V) \approx 0.72$ . Second, thanks to the NASA Extragalactic Database (NED), we gathered information about the Galactic absorption which affects objects with lines of sight near that of HG 031203. We found four galaxies in a radius of  $10'$  from the host, with a mean  $E_{\text{MW}}(B - V) \approx 0.72$ . Consequently, we consider  $E_{\text{MW}}(B - V) \approx 0.72$  to be a good estimate of the Galactic absorption in the direction of the burst.

Adopting  $E_{\text{MW}}(B - V) \approx 0.72$ , we estimate for each spectrum the intrinsic reddening through comparison of Balmer line decrements under the assumption of Case B recombination (Osterbrock & Ferland 2006). We assumed a Cardelli et al. (1989) extinction law with  $R_V = 3.1$  for both our Galaxy and HG 031203. The use of a Small Magellanic Cloud extinction law for the host would not significantly affect the results we obtain. Table 6 shows, for each night of observation, the observed Balmer line ratios and the intrinsic reddening ( $E_{\text{HG}}(B - V)$ ) derived from them. The errors are calculated by simply propagating the uncertainties of the measured Balmer ratios. Also shown is the reddening value estimated from Prochaska et al. (2004) data. We re-analysed their spectrum in order to have a homogeneous dataset spanning the longest possible temporal range. In

**Table 6.** HG 031203 intrinsic reddening values and hydrogen Balmer line ratios from which it has been derived. Reliable observed emission line fluxes has been used only. We assumed  $E_{\text{MW}}(B - V) = 0.72$ .

Date	H $\alpha$ /H $\beta$	H $\beta$ /H $\gamma$	H $\gamma$ /H $\delta$	$E_{\text{HG}}(B - V)$	
03/12/06 <sup>a</sup>	8.942	3.727	2.623	0.5516	$\pm 0.0167$
03/12/20	7.937	3.662	2.391	0.4329	$\pm 0.0471$
03/12/30	7.449	3.712	–	0.3843	$\pm 0.0446$
04/03/02	7.451	3.803	2.217	0.3806	$\pm 0.0874$
04/03/16	8.330	3.166	–	0.3846	$\pm 0.1904$
04/09/20	8.086	3.697	2.293	0.4548	$\pm 0.0467$

<sup>a</sup> Re-analysis of the Prochaska et al. (2004) spectrum.

particular, the intrinsic extinction correction we derive for this spectrum is higher than the value Prochaska et al. (2004) found ( $E_{\text{HG}}(B - V) = 0.39$ ). We believe that this is mainly related to the different Galactic absorption assumed by them in the direction of the burst. A minor role is played by their use of a single extinction law, a procedure that neglects the limited effects caused by the non-zero redshift of the host galaxy.

We are now able to apply the derived extinction corrections to the observed emission-line fluxes listed in Table 4 and Table 5. In the same tables, the extinction-corrected fluxes and errors are also reported. From the badly constrained Galactic extinction we expect an additional uncertainty of  $\sim 15\%$ , ranging from 10 to 25% at 9000 and 4000 Å respectively. Extinction and  $K$ -corrected absolute magnitudes of HG 031203 are listed in Table 2.

#### 4. Nebular parameters and metallicity

In this section we first derive the physical features of the nebular region within HG 031203: emission-lines ratios, electron temperature, and electron density. Then we examine the chemical abundances of the elements.

**Table 7.** Diagnostic line intensity ratios for HG 031203.

	$([\text{OIII}]_{5007})/(\text{H}\beta_{4861})$	$([\text{NII}]_{6583})/(\text{H}\alpha_{6563})$
VLT <sup>a</sup>	0.80	-1.28
	$([\text{SII}]_{6716+6731})/(\text{H}\alpha_{6563})$	$([\text{OI}]_{6300})/(\text{H}\alpha_{6563})$
VLT	-1.50	-2.00

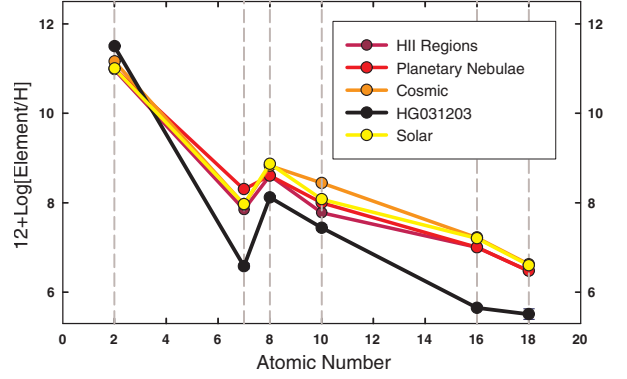
<sup>a</sup> VLT averaged value.

Table 7 lists the diagnostic line-intensity ratios corrected for reddening obtained from VLT spectra taken on 2003 Dec. 20th, 2003 Dec. 30th, 2004 March 2nd, and 2004 Sep. 20th. The line-intensity ratios for emission-line galaxies have been extensively discussed in the literature; in particular, adopting the samples of HII regions and active galactic nuclei (AGNs) presented by Osterbrock & Ferland (2006) as reference samples, it is easy to see that all of the ratios obtained for HG 031203 are typical of starburst galaxies, in agreement with Prochaska et al. (2004). This fact, along with the observation that all of the lines are narrower than the instrumental resolution, allows us to exclude the presence of an AGN as source of ionization. Moreover, it establishes a strong link between HG 031203 and star formation; the emission lines are produced by HII regions.

Following the standard nebular theory discussed by Osterbrock & Ferland (2006), we know that the electron density may be assessed by observing the effects of collisional de-excitation; while the electron temperature may be determined from measurements of intensity ratios of lines emitted by a single ion from two levels having considerably different excitation energies. From the [S II] and [O III] emission-line ratios averaged over the four VLT spectra, we find for HG 031203 an electron density  $N_e = 160 \pm 20 \text{ cm}^{-3}$  and a temperature  $T_e = 12400 \pm 100 \text{ K}$  (quoted error bars include only the measurement uncertainties). An additional uncertainty of the order of 2% is expected to affect our electron temperature estimate because of the badly constrained Galactic color excess. However, we note the substantial agreement between our results and those of Prochaska et al. (2004) assuming a two-zone model for the temperature: for the moderate zone they derive  $T_{\text{mod}} = 13400 \pm 2000 \text{ K}$ , and assuming  $T_{\text{low}} = 12900 \text{ K}$  they find  $N_e \approx 300 \text{ cm}^{-3}$  (the value adopted for both zones).

Next, we estimate the relative elemental abundances for He, N, O, Ne, S, Ar following the procedure detailed in Osterbrock & Ferland (2006). Atomic parameters (recombination and collision excitation coefficients) have been interpolated to the ISM temperature and density estimated above. Ionization correction factors of Izotov et al. (1994) have been used in order to account for unobserved stages of ionization, while the solar reference values come from Osterbrock & Ferland (2006). Our results are shown in Table 8.

For each element we report the weighted-average value over the four VLT spectra; uncertainties were calculated using the standard theory of error propagation. The badly constrained Galactic color excess is source of systematic errors estimated to be 0.03 dex at most. Figure 2 shows the relative elemental abundances of HG 031203 as a function of the atomic number,  $Z$ . Solar and cosmic abundances, and abundances of H II regions and planetary nebulae are also plotted for comparison. From this figure, it is clear that GRB 031203 occurred in a low-metallicity environment. We will quantify this statement in Sect. 8. Here we only note that HG 031203 is characterised by  $12 + \log(\text{O}/\text{H}) = 8.12 \pm 0.04$ . To this uncertainty, a further error of 0.03 dex needs to be added, to account for the uncertainty in the dust correction.



**Fig. 2.** Relative elemental abundances as function of the atomic number. Reference values for other environments taken from Osterbrock & Ferland (2006).

## 5. Star formation

With a redshift  $z = 0.1054$ , HG 031203 has a luminosity distance  $D_L = 473 \text{ Mpc}$ . According to Kennicutt (1998), the  $\text{H}\alpha$  luminosity derived from Tables 4 and 5 and corrected for slit losses corresponds to a star-formation rate  $\text{SFR}(\text{H}\alpha) = 12.9 \pm 2.2 M_\odot \text{ yr}^{-1}$  (value averaged over the four VLT spectra). The uncertainty arising from the badly constrained Galactic color excess is estimated to be  $\sim 13\%$ .

While we caution the reader that the uncertainty reported here does not account for the uncertainties in the SFR calibration, estimated to be  $\sim 30\%$  (Kennicutt 1998), we also stress the substantial agreement between the Prochaska et al. (2004) results and ours. For HG 031203 they find  $\text{SFR}(\text{H}\alpha) = 11 M_\odot \text{ yr}^{-1}$ , a lower limit to the total SFR because of slit losses and the possible presence of regions of star formation enshrouded in dust. Parenthetically, we note that Watson et al. (2004) derived from X-observations an upper limit to the HG 031203 SFR of  $150 \pm 110 M_\odot \text{ yr}^{-1}$ .

We can further characterize the star-formation activity of HG 031203 through the analysis of two other parameters: the rest-frame equivalent width of the  $\text{H}\alpha$  emission line and the specific star-formation rate (SSFR). The galaxy is notable for its rather strong  $\text{H}\alpha$  emission; we measure  $EW_{\text{rest}}(\text{H}\alpha) = 760 \pm 80 \text{ \AA}$  after the underlying supernova continuum has faded away. We will contrast the properties of HG 031203 with local samples of galaxies in Sect. 8; however, here we note that this is an extremely high value, significantly larger than that of normal star-forming galaxies in the local universe.

Another valuable diagnostic of star formation is the SSFR, here defined as the ratio of  $\text{H}\alpha$  to  $B$ -band luminosity. For HG 031203 we measure  $M_B = -21.00 \pm 0.39 \text{ mag}$  (see Table 2). With an extinction-corrected  $\text{H}\alpha$  luminosity of  $1.6 \times 10^{42} \text{ erg s}^{-1}$ , HG 031203 is then characterised by  $\text{SSFR} \approx 0.1$ , much higher than the average SFR per unit  $B$ -band luminosity of ordinary local galaxies.

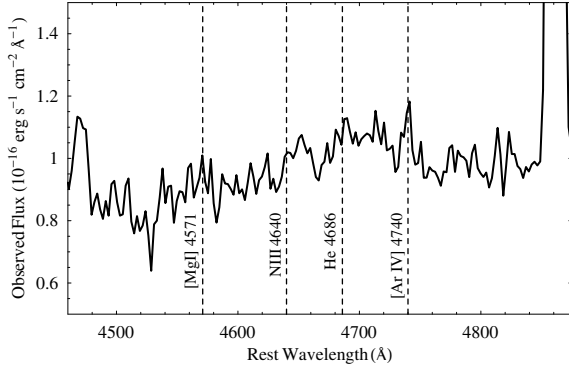
We will quantitatively discuss this results in Sect. 8.

## 6. A WR bump?

In this section we investigate the spectra of HG 031203 for possible signatures of Wolf-Rayet (WR) stars emission, as previously claimed by Hammer et al. (2006). We pay particular attention to the presence of broad emission at  $4686 \text{ \AA}$  due to He II, the strongest line in the optical for WR stars along with  $4650 \text{ \AA}$  C III and  $5808 \text{ \AA}$  C IV (Conti & Massey 1989). Furthermore, we

**Table 8.** Relative elemental abundances for HG 031203.

Element	He	N	O	Ne	S	Ar
Abundances	$11.50 \pm 0.04$	$6.58 \pm 0.06$	$8.12 \pm 0.04$	$7.44 \pm 0.06$	$5.65 \pm 0.04$	$5.51 \pm 0.12$


**Fig. 3.** Result of the stacking of the host galaxy spectra taken on March 2nd and September 20th, shown close to the region supposed to be populated by WR lines.

investigate the spectra for the presence of other WR features, the most common of which is  $4640 \text{ \AA}$  N III. This is the only WR emission line, aside from  $4686 \text{ \AA}$  He II which is clearly identified in several WR galaxies (Conti 1991). Our results are shown in Fig. 3: in order to increase the signal to noise ratio and better address the potential presence of WR signatures, we stacked our latest spectra (the spectra taken on December 20th and 30th were significantly contaminated by the SN emission). From this figure it is clear that the identification of the He II and  $4640 \text{ \AA}$  N III emission lines is uncertain.

## 7. Continuum emission

So far we focussed on the line radiation emitted by HG 031203. In this section we analyse the continuum-emission properties of the host, with the aim of further characterizing the large-scale environment of the nearby GRB event.

The observed continuum consists of three components: stellar, supernova, and nebular. We have no evidence for a non-thermal source; the measured diagnostic line-intensity ratios corrected for reddening (see Table 7) clearly indicate that HG 031203 is an object dominated by photoionization, with line ratios typical of starburst or H II galaxies.

In order to exclude the SN contribution, we restrict our analysis to the VLT spectra taken in March and September 2004. For the nebular continuum, we identify two different sources of emission: the recombination process and the two-photon decay of the  $2^2S$  level of hydrogen. Recombination processes lead to the emission of a rather weak continuum in free-bound and free-free transitions. Since hydrogen is the most abundant element, the H I continuum is the strongest; on the other hand, since the He II lines are missing in HG 031203 spectra, we expect negligible contribution from this ionization stage. Recombination emission coefficients and emission coefficients of two-photon decay have been interpolated to the interstellar medium (ISM) parameters calculated above (Osterbrock & Ferland 2006). We then normalized the theoretical nebular continuum to the observed He I and H I line fluxes (Tables 4 and 5). Results are shown in Fig. 4. Since the nebular spectrum is redder than the stellar spectrum, a bluer spectrum results if the nebular contribution is removed.

In order to obtain more information about the HG 031203 stellar populations, we analyse the continuum contribution that is stellar in origin. We adopt a simplified procedure: a detailed model, beyond the scope of this paper, is in progress. Moreover, we handle a limited portion of the host spectral energy distribution (SED). An ultraviolet spectrum would be of particular interest to investigate the ionizing continuum of the galaxy. We adopt a Kroupa et al. (1993) initial mass function (IMF). Next, we assume for simplicity that the observed stellar continuum is due to main-sequence stars characterized by black-body emission, the main-sequence mass-temperature relation, and the main-sequence mass-radius relation. As a consequence, according to our simplified model, the host spectrum can be written as:

$$F_{\lambda_{\text{obs}}} = \frac{(1+z)^{-1}}{4\pi D_L^2} \int_{M_i}^{M_f} \xi(m) BB_{\lambda}(T(m)) 4\pi r^2(m) dm \quad (1)$$

where:

$$\lambda = \frac{\lambda_{\text{obs}}}{(1+z)} \quad (2)$$

$F_{\lambda_{\text{obs}}}$	Flux per unit observed wavelength
$D_L$	Luminosity distance corresponding to a redshift $z$
$\xi(m)$	IMF
$BB_{\lambda}(T(m))$	Black body energy distribution at temperature $T$
$r$	Stellar radius
$M_i, M_f$	Lower and upper end of the mass distribution. We use $M_i = 0.08 M_{\odot}$ ; $M_f =$ free parameter of the model.

A  $(1+z)^{-1}$  term is needed in order to account for the cosmological frequency or wavelength folding. Finally, we fit the stellar continuum leaving the IMF normalization and the upper end of the mass distribution as free parameters of our model. A best-fit HG 031203 SED is derived.

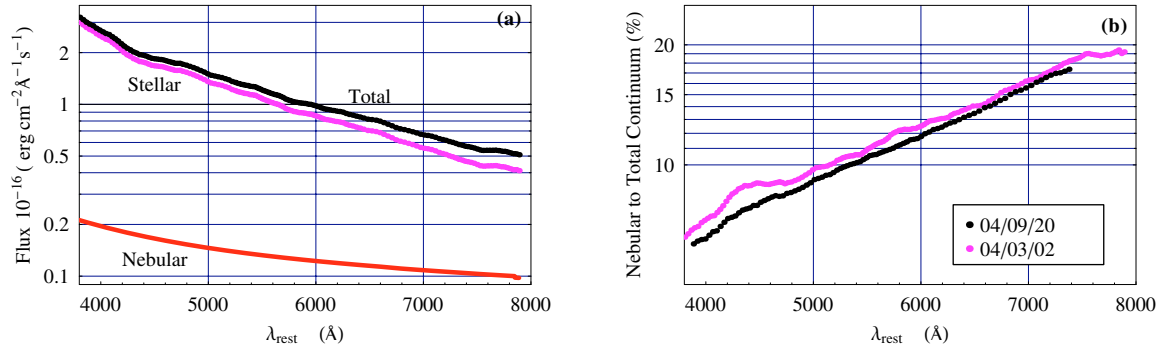
To improve the sensitivity of our model to the unobserved ionizing continuum of the host, we consider the following complementary approach. From the standard theory of recombination, well described by Osterbrock & Ferland (2006), it is also possible to show that:

$$F(\text{H}\beta) = \frac{\alpha_{\text{H}\beta}^{\text{eff}}(\text{H}, T)}{\alpha_B(\text{H}, T)} \int_0^{\lambda_0} \frac{\lambda}{\lambda_{\text{H}\beta}} F_{\lambda} d\lambda \quad (3)$$

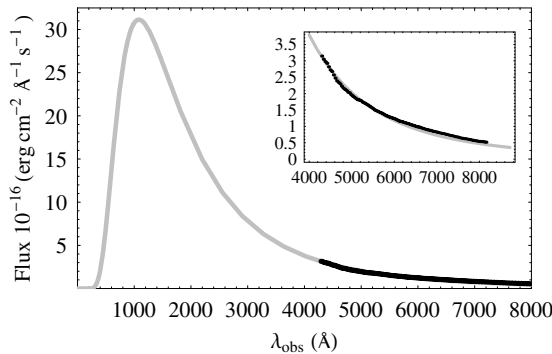
where:

$F(\text{H}\beta)$	Emission line flux of the hydrogen Balmer $\beta$ line
$F_{\lambda}$	Flux per unit wavelength estimated from $F_{\lambda_{\text{obs}}}$ , Eq. (1)
$\alpha_{\text{H}\beta}^{\text{eff}}(\text{H}, T)$	Effective recombination coefficient for the hydrogen Balmer $\beta$ line at temperature $T$ (Osterbrock & Ferland 2006)
$\alpha_B(\text{H}, T)$	Recombination coefficient for hydrogen at temperature $T$ (Osterbrock & Ferland 2006)
$\lambda_0$	Ionization threshold.

Comparing the predicted H $\beta$  flux (estimated using the previous relation) to the observed H $\beta$  flux (from Table 4), and then



**Fig. 4.** **a)** Nebular continuum, stellar continuum and total continuum of HG 031203 obtained from VLT observations taken in March 2004. We find analogous results for the host continuum observed in September 2004. **b)** Ratio of nebular to total continuum for the VLT observations acquired in March and September 2004. Extinction corrected data are shown.



**Fig. 5.** Grey line: theoretical stellar spectral energy distribution of the host galaxy of GRB 031203. The stellar continuum estimated from the observations taken in September 2004 is also shown for comparison (black line).

normalizing the free parameters of our model to the observed  $H\beta$  flux, we finally derive:

$$\begin{cases} M_f \approx 25 M_\odot \\ M_{\text{tot}} \approx 10^9 M_\odot \end{cases} \quad (4)$$

where  $M_f$  is the upper end of the stellar mass distribution, while  $M_{\text{tot}}$  is the total stellar mass of the emitting volume we observe. Our results are shown in Fig. 5. Given the simplified method used, we expect our results to be reliable within a factor of two.

## 8. Discussion

Our analysis of HG 031203 reveals a small, metal-poor star-forming galaxy. In this section we will discuss the physical properties of the host, contrasting its characteristics with a complete sample of  $\sim 1000$  local ( $z \leq 0.1$ ), normal, star-forming galaxies from KISS (Salzer et al. 2000).

In order to carry out a statistically significant analysis, the largest sample of local LGRB HGs with associated SNe will be considered. This sample includes HG 980425, HG 030329, HG 031203, and HG 060218. We summarize the observed properties of the hosts in Table 9.

Recently, two additional LGRBs have been discovered at low redshift: GRB 060505 at  $z = 0.09$  (Fynbo et al. 2006) and GRB 060614 at  $z = 0.125$  (Della Valle et al. 2006; Gal-Yam et al. 2006). However, these bursts were somewhat peculiar, not showing any SN component down to deep limits, and there is intense debate concerning their origin (e.g., Gehrels et al. 2006; King et al. 2007). We therefore chose to exclude their host galaxies from the present analysis.

**Table 9.** Properties of the LGRB/SN host galaxies of the local universe.

	HG 980425	HG 030329	HG 031203	HG 060218
$z$	0.0085 <sup>f</sup>	0.1685 <sup>f</sup>	0.10536 <sup>h</sup>	0.0335 <sup>d</sup>
$12 + \log(\text{O}/\text{H})$	8.39 <sup>a</sup> 8.25 <sup>b</sup>	7.8 <sup>c</sup>	8.12 <sup>h</sup>	8.0 <sup>d</sup>
$M_B$ mag	-17.65 <sup>f</sup>	-16.5 <sup>g</sup>	-21.00 <sup>h</sup>	-15.86 <sup>d</sup>
SFR( $H\alpha$ ) $M_\odot \text{ yr}^{-1}$	0.35 <sup>f</sup>	0.40 <sup>f</sup>	12.32 <sup>h</sup>	>0.07 <sup>e</sup>
SSFR	0.05	0.19	0.1	>0.04

<sup>a</sup> WR Region Hammer et al. (2006),  $T_e$  method, <sup>b</sup> SN Region Hammer et al. (2006),  $T_e$  method, <sup>c</sup> Thöne et al. (2006),  $R_{23}$  method, <sup>d</sup> Modjaz et al. (2006),  $R_{23}$  method, <sup>e</sup> Ferrero et al. (2006), <sup>f</sup> Sollerman et al. (2005), <sup>g</sup> Gorosabel et al. (2005), <sup>h</sup> This work.

### 8.1. Intrinsic extinction

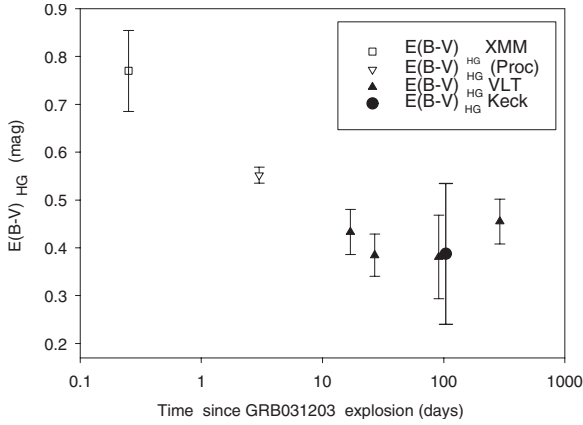
Here we gather all of the available information about the intrinsic extinction of HG 031203. Our goal is to test the possibility that the extinction changed with time. Figure 6 shows the data. In particular, the first point shown is derived from XMM-Newton observations: from the X-ray data Vaughan et al. (2004) estimate a hydrogen column density  $N_{\text{H}} = (8.8 \pm 0.5) \times 10^{21} \text{ cm}^{-2}$ . Assuming the standard hydrogen column density vs. reddening correlation,

$$E(B - V) = \frac{N_{\text{H}}}{5.9 \times 10^{21} \text{ cm}^{-2}}, \quad (5)$$

we derive a total reddening  $E(B - V)_{\text{TOT}} = 1.49 \pm 0.08$  in the direction of the burst. Adopting a single extinction law and  $E(B - V)_{\text{MW}} = 0.72$ , this would formally correspond to an intrinsic reddening  $E(B - V)_{\text{HG}} = 0.77 \pm 0.08$ . The second point in the plot is derived from the re-analysis of the Prochaska et al. (2004) spectrum.

The X-ray observations started only 6 hours after the burst, while the last VLT spectrum is from  $\sim 9$  months after the explosion. On the other hand, the value derived from the hydrogen column density strongly depends on the assumed dust-grain size and gas-to-dust ratio. In particular, increasing one of these two parameters, we would obtain a smaller  $E(B - V)/N_{\text{H}}$  ratio and a larger  $R_V$  value (Maiolino et al. 2001). The gas-to-dust ratio is expected to have substantial variations in the outskirts of the Galactic plane (Burton 1988), regions that the X-ray signal from GRB 031203 had to cross. For this reason we are skeptical about the reliability of the intrinsic reddening estimate derived from X-ray observations.



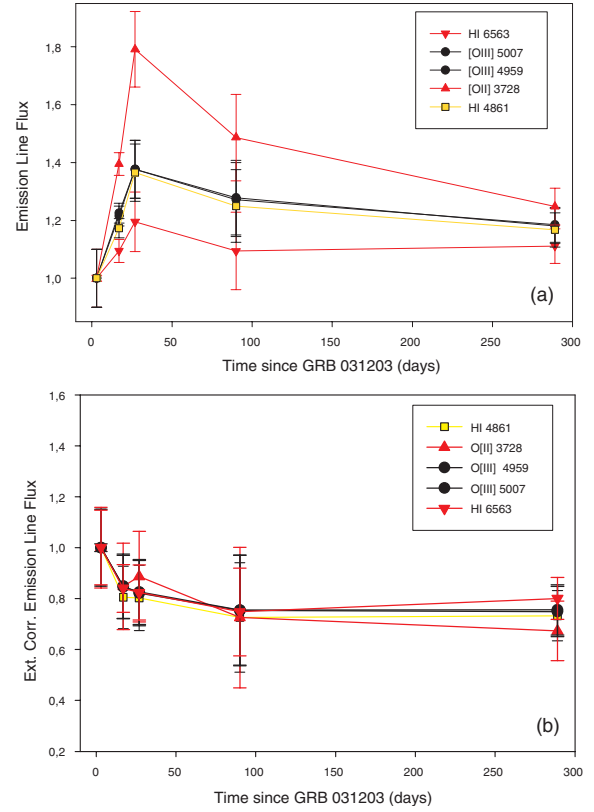


**Fig. 6.** Intrinsic reddening value  $E_{\text{HG}}(B-V)$  for HG 031203 as a function of time elapsed from GRB explosion. While the first point is derived from X-ray observations, all the other values are estimated through comparisons of Balmer line ratios, assuming  $E_{\text{MW}}(B-V) = 0.72$ . See Table 6 for the numerical values of the data shown.

Apart from the X-ray data point, there seems to be a tendency of the HG 031203 reddening value to decline with time. However, we must also consider that this conclusion relies completely on the reliability of the value of  $E(B-V)_{\text{HG}}$  derived from our analysis of the Prochaska et al. 2004 spectrum. Our VLT  $E(B-V)_{\text{HG}}$  estimates are consistent with no time evolution of the parameter. Moreover, the Balmer decrements we used to calculate the extinction corrections are particularly sensitive to small errors in the line-fitting procedure. These factors seem to cast doubt on the variable intrinsic reddening hypothesis.

In order to better address this issue we considered the potential evolution with time of emission line fluxes. The observed line fluxes are expected to evolve because of the joint action of the gradual ionization of the medium by the GRB radiation (we refer the reader to Perna & Loeb 1998; Perna et al. 2000 and references therein) and a time-dependent intrinsic extinction. Given the present set of data we can check this hypothesis on a month time scale. To this end, it is necessary to correct the emission line fluxes for slit losses. A relative correction of  $\approx 10\%$  has been applied to our VLT fluxes to account for this fact. Before applying the extinction corrections (Fig. 7a), we find that 38% of the emission lines with firm identification shows no time evolution at  $1\sigma$  confidence level; 71% at  $2\sigma$  and 81% at  $3\sigma$ . Correcting for the Galactic and the intrinsic reddening (using the different  $E_{\text{HG}}(B-V)$  values listed in Table 6) the situation changes as follows (Fig. 7b): 57% of the lines are consistent with the no-evolution hypothesis at  $1\sigma$ ; 95% at  $2\sigma$  while all the emission lines show no-evolution at  $3\sigma$ . Non-corrected fluxes show variations of a factor of 2 at most, (see Fig. 7) with the most consistent evolutions detected at the shortest wavelength and with the peak of the variation occurring approximately 30 days after the GRB explosion (epoch at which Malesani et al. 2004 detect the peak of the SN2003lw light curve). While the wavelength-dependence implicitly suggests the time evolution of the intrinsic color excess to be the source of the limited flux evolution we detect, we conclude the absence of compelling observational evidence of emission line fluxes evolution with time on a typical month-scale.

Hence, the detection of the “cleaning action” of the burst remains at low significance level.



**Fig. 7.** Evolution of the five brightest emission lines fluxes. Emission line fluxes have been normalized to the observations taken on December 6th (re-analysed Prochaska et al. 2004 spectrum). Data have been corrected for the different slit losses. **a)** Non extinction corrected data; **b)** Extinction corrected data.

## 8.2. Metallicity

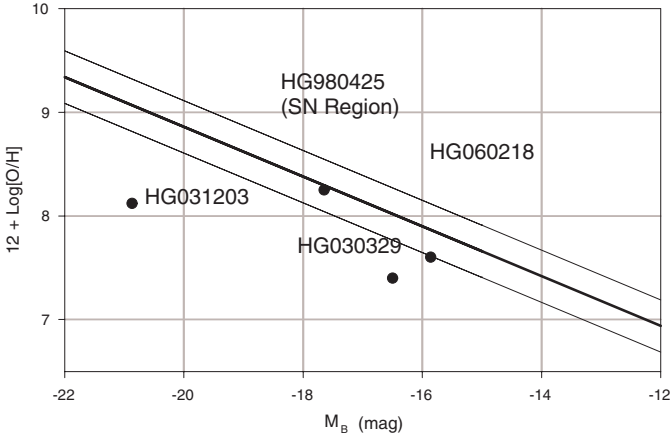
With  $12 + \log(\text{O}/\text{H}) = 8.12$ , HG 031203 has a low metallicity (Fig. 2). In order to quantify this result, we contrast the hosts properties against a sample of ordinary star-forming galaxies. For the KISS galaxy sample, Melbourne et al. (2004) find a metallicity vs.  $B$ -band luminosity relation expressed by

$$12 + \log(\text{O}/\text{H}) = (4.059 \pm 0.17) - (0.240 \pm 0.006)M_B, \quad (6)$$

with a root-mean-square (rms) deviation of residuals of 0.252 dex. Metallicities have been estimated by Melbourne et al. (2004) using the  $T_e$  method. Where not possible, the authors used the standard  $R_{23}$  method improved by the introduction of the  $p_3$  factor (Pilyugin 2000). In this way the  $R_{23}$  method was found to correlate with the  $T_e$  method to within 0.1 dex for starbursts with metallicities below  $12 + \log(\text{O}/\text{H}) = 7.9$ . Results obtained in this way were used to calibrate relations between metallicity and emission-lines ratios.

According to the above relation, with  $M_B \approx -21$  (Sect. 5) HG 031203 would have had a relative oxygen abundance  $12 + \log(\text{O}/\text{H}) \approx 9$ , 0.9 dex above the value we measure. Actually, the host metallicity is lower than that of more than 99% of all KISS galaxies with  $M_B \leq -21$ .

Figure 8 offers a graphic view of this offset, interpreted by Prochaska et al. (2004) as a signature of a very young star-forming region. These authors speculate that HG 031203 has been observed prior to the production and/or distribution of metals into its nebular regions. From the same figure it is also clear that this is not a property shared by all the HGs of the local universe with associated SN: HG 060218 and HG 980425 follow the



**Fig. 8.** Metallicity–luminosity relationship for KISS galaxies (thick line) and for local LGRB HGs. For HG 030329 and HG 060218 we applied the metallicity conversion of L. J. Kewley & S. L. Ellison (2007, in preparation) to the  $R_{23}$  estimates of Table 9. Thin lines mark the rms 0.25 dex deviation of residuals about the fit. We refer the reader to Melbourne et al. (2004) for details.

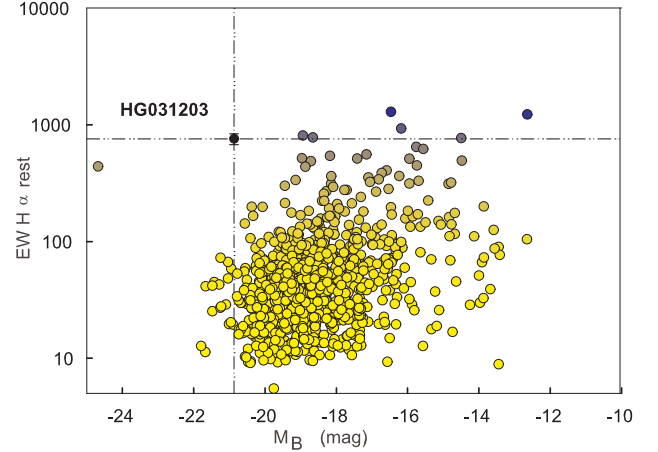
KISS trend within the scatter, while HG 030329 falls outside if we prefer the lower branch metallicity estimate as indicated by Stanek et al. (2006) and Thöne et al. (2006). We therefore do not find a compelling evidence for all the HGs to be characterised by a substantially lower metallicity.

A similar conclusion has been independently derived by Wolf & Podsiadlowski (2007) analysing a subsample of the Fruchter et al. (2006) data and considering only HGs in the redshift interval 0.2–1. These authors find all of the hosts to be within  $\pm 1/3$  dex of the metallicity–luminosity relation by Kobulnicky & Kewley (2004) and conclude that there is no metallicity bias within the statistical significance of five objects. Using a large sample of local luminous star-forming SDSS galaxies previously studied by Tremonti et al. (2004) as a reference sample, Stanek et al. (2006) conclude that local LGRB/SN hosts have oxygen abundances much lower than would be expected if local GRBs traced local star formation independently of metallicity. Indeed, a larger and more representative sample of LGRB hosts with well-assessed physical properties is needed before being able to definitively answer the host peculiarity question.

Metallicity seems to play a central role in the production of a LGRB event: theoretical models favour progenitors of low metallicity. Finding a dependence of the LGRB rate on host metallicity would therefore be of particular interest. Stanek et al. (2006), after investigating the physical properties of LGRB/SN hosts with  $z \leq 0.2$ , find a host-metallicity threshold for producing cosmological GRBs of  $12 + \log(\text{O}/\text{H}) \approx 8.0$ .

However, after developing a Monte Carlo code to generate LGRB events within cosmological hydrodynamical simulations consistent with the  $\Lambda$ CDM model, Nuza et al. (2007) find no tight correlation between the O/H abundance of the LGRB progenitor star and the mean metallicity of the HG. From an observational point of view, even spectroscopic but spatially unresolved measurements of a mean host metallicity do not directly reflect the metallicity of the immediate burst environment (Wolf & Podsiadlowski 2007).

Moreover, uncertainties exist with respect to the calibration of the various methods used to measure the oxygen abundances: direct measurement from observed oxygen emission lines (Osterbrock & Ferland 2006);  $R_{23}$  indicator (Pagel et al. 1979); electron temperature ( $T_e$ ) method (see, e.g.,



**Fig. 9.** Equivalent width at rest of the  $H\alpha$  line for HG 031203 and for a complete sample of normal star-forming galaxies of the local universe (KPNO International Spectroscopic Survey of galaxies, Salzer et al. 2000) as a function of absolute  $B$ -band magnitude. KISS data are not extinction corrected.

Kennicutt et al. 2003); and the recently developed O II<sub>RL</sub> method (Peimbert et al. 2006).

Finally, it is not well established whether the oxygen abundance is representative of other elements: different elements might provide much of the opacity in stellar winds and atmospheres, affecting in this way the stellar evolution and the possible LGRB production.

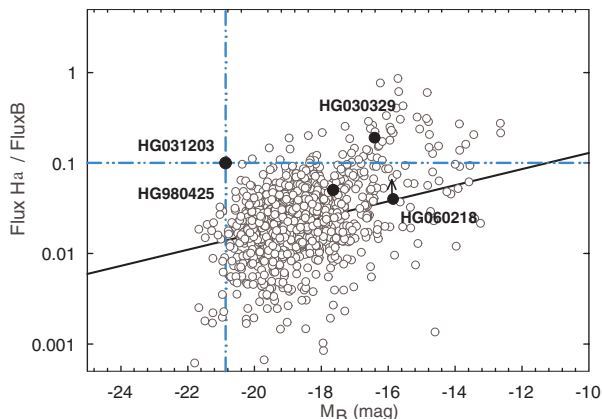
### 8.3. Star formation activity of local LGRB HGs

HG 031203 is notable for its very intense star-formation activity. First, this galaxy has  $\text{SFR} > 10 M_{\odot} \text{yr}^{-1}$ , greater than 98% of all low-redshift ( $z \leq 0.1$ ) galaxies (Prochaska et al. 2004; Nakamura et al. 2004). Second, HG 031203 exhibits a significant rest-frame equivalent width of the  $H\alpha$  line, increasing from 2003 December to 2004 September because of the decreasing underlying SN 2003lw continuum. Considering the SN contribution in September to be negligible, we measure for HG 031203  $EW_{\text{rest}}(H\alpha) = 760 \pm 80 \text{ \AA}$ .

Figure 9 compares this value directly with the same quantity measured for local, normal, star-forming galaxies from KISS. It is clear that HG 031203 shows an  $EW_{\text{rest}}(H\alpha)$  value significantly larger than that of ordinary galaxies at the same redshift; it is larger than that of 99% of all galaxies in the reference sample.

Third, the specific star formation rate (SSFR) of the host is also remarkable. As before, we compare the extinction corrected  $H\alpha/B$ -band luminosity of HG 031203 against the KISS galaxies (Fig. 10).

KISS data are not extinction-corrected; hence, they provide upper limits to the  $H\alpha/B$ -band flux ratio. In spite of this, HG 031203 falls in the upper end of the distribution and exhibits a SSFR greater than that of 98% of all KISS galaxies. Furthermore, if we consider the SSFR of the largest sample of local LGRB/SN HGs (reference data are reported in Table 9), we find that all of the hosts are in the upper part of the panel. This fact reveals a trend for LGRB/SN hosts to be characterized by SSFRs which are larger than those of ordinary star-forming galaxies at similar redshifts, as previously reported by Christensen et al. (2004).



**Fig. 10.** SSFRs of local GRB hosts against a complete sample of normal star forming galaxies of the local universe (KISS galaxies) as a function of absolute  $B$ -band magnitude. KISS data are not extinction corrected and provide therefore upper limits to the parameter. Thick line: KISS data best fit line.

#### 8.4. Wolf-Rayet emission in HG 031203 spectra?

A deep understanding of the GRB production mechanism requires us to study GRB environments in detail. Wolf-Rayet (WR) stars are the favoured GRB progenitors in the collapsar model (Woosley et al. 1999; Mészáros 2002); detailed stellar evolution models of WR stars are consistent with the conditions for GRB production via collapsar, as shown by Hirschi et al. (2005). In particular, the evolution of these stars is able to reproduce the conditions for black hole formation and for the loss of the hydrogen-rich envelope (as is expected if GRBs originate from SNe Ib or Ic). Furthermore, these stars are able to retain sufficient angular momentum to form an accretion disk around the black hole. Finally, if only stars of the particular subtype WO (Conti 1991) are considered, then the GRB production rate can be reproduced (Hirschi et al. 2005).

Following Conti (1991), WR galaxies are defined to be those galaxies whose integrated spectra show a broad ( $FWHM \geq 10 \text{ \AA}$ ) emission feature around  $4650 \text{ \AA}$ , attributed to WR stars. Along with the He II  $\lambda 4686$  line, we know that C III  $\lambda 4650$  C IV  $\lambda 5808$  are the strongest optical lines of WR stars while N III  $\lambda 4640$  is one of the most common feature of WR galaxies. Examples of typical WR-galaxy spectra are shown by Guseva et al. (2000). Investigating the spectrum of the GRB 031203 host taken in September 2004, Hammer et al. (2006) detect a blue bump around the He II  $\lambda 4686$  line, and conclude that WR stars are present in the host galaxy. While we also detect an emission bump around the expected position of the He II line in each of the spectra we analysed, we consider dubious the identification of the He II  $\lambda 4686$  and N III  $\lambda 4640$  lines (see Fig. 3). We do not exclude that this bump of emission might in principle arise from blending of faint and broad emission lines emitted by WR stars; however we emphasize that it is not possible to classify the HG of GRB 031203 as a WR galaxy from the detected emission lines.

## 9. Conclusions

HG 031203 offers a precious opportunity to study in detail the environment of a nearby LGRB. Here we show that this galaxy is notable for its star-formation activity, with  $EW_{\text{rest}}(\text{H}\alpha) = 760 \pm 80 \text{ \AA}$  and  $\text{SFR}(\text{H}\alpha) = 12.9 \pm 2.2 M_{\odot} \text{ yr}^{-1}$ ; we believe these values to be signatures of the very intense burst of star

formation that is occurring in this galaxy. Furthermore, we suggest that the peculiarity of LGRB HGs is that their star-formation efficiencies (SSFR) are significantly higher than in ordinary star-forming galaxies at the same redshift.

We do not find compelling evidence for all the LGRB HGs of the local universe to have a substantially lower metallicity when compared to normal star forming galaxies with the same  $B$ -band luminosity. However, HG 031203 is a clear outlier, with its exceptionally low metallicity.

After searching for possible WR emission features in our spectra, we conclude that the detection and identification of typical WR emission lines is uncertain.

Finally, our data suggest, but do not clearly support, the possibility that the intrinsic extinction of HG 031203 evolved with the time as a consequence of the exposure of dust grains to the hard radiation of the GRB.

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