Explosion of a massive, He-rich star at z=0.16

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Abstract. We present spectroscopic and photometric data of the peculiar type Ib supernova 2001gh, discovered by the *Southern inTermediate Redshift ESO Supernova Search* at a redshift z=0.16. SN 2001gh has high luminosity at maximum, while the light curve shows a broad, delayed peak. An early-time spectrum shows an almost featureless blue continuum with a few weak P-Cygni lines that we attribute to He I. He I lines remain the only spectral features visible in another spectrum obtained one month later. Three possible scenarios are considered: a massive and energetic progenitor with $M_{ejecta} \sim 30 M_\odot$, E $\sim 6x10^{52}$ erg and earlier explosion date; a moderate-mass progenitor with $M_{ejecta} \sim 15 M_\odot$, M_{Ni} = 0.65 $M_\odot$ and E $\sim 18x10^{51}$ erg; or a more canonical SN Ib with a dense, circumstellar shell.

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SN 2001GH

SN 2001gh was discovered by [1] on 2001 November 12.19 UT, in the field labelled as J1888 (*Southern inTermediate Redshift ESO Supernova Search*, [2]). The SN, hosted in an anonymous galaxy, was located at $\alpha = 00^h57^m03\overset{s}{.}63$, $\delta = -27^o42'32\overset{''}{.}90$ (J2000.0). SN 2001gh had a blue and featureless spectrum and was tentatively classified a type II supernova at very early phases, although this classification has been now revised.

SPECTROSCOPY

Two spectra of SN 2001gh were taken on November 22.24 and December 20.16 at the ESO Very Large Telescope UT2 with FORS1 (using grism 300V+GG435). The most notable feature in the first spectrum is the very blue continuum, with almost no sign of individual lines, except for a few weak and broad P-Cygni profiles around 4470, 5000, 5870, 6600 and 7065 Å that, contrary to the original classification, we now attribute to He I. The second spectrum (obtained approximately a month later) shows a slightly redder continuum, which is possibly indicative of a temperature decrease. In addition, the He I P-Cygni lines are still the only features visible in the spectrum. We propose to reclassify this SN like a peculiar Type Ib. Considering the position of the emission peaks of the He I lines, we are able to fix the SN redshift as z=0.16 ± 0.01. In Fig. 1–(a) we show a comparison of these spectra with the co-eval SN 2002hy (peculiar

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SN Ib, unpublished spectrum), SN 2000H (SN Ib, [3]), and SN 1999em (SN IIP, [4]). The comparison confirms that SN 2001gh is a peculiar SN Ib, and the pronounced P-Cygni profile of Hα characterizing spectra of SNe II (SN 1999em) is not unequivocally detected in SN 2001gh. By contrast, it is evident the overall similarity with SN 2002hy (Fig. 1–(a), top panel). These two SNe show almost featureless spectra with He I lines with comparable profiles. The most remarkable difference is that the P-Cygni profile around 5870 Å is narrower in SN 2001gh than in SN 2002hy.

The velocities derived from the position of the P-Cygni minima of the most prominent He I line at 5876 Å (the low S/N of our spectra does not allow us to properly measure the velocity of other lines) are $\sim$ 7400 and 6000 km s^{-1} – for the early and late spectra of SN 2001gh, respectively.

PHOTOMETRY

The light curve of SN 2001gh is rather peculiar. Given the high redshift estimated for this SN, the visible light from the object has been K-corrected, and therefore, the observed V- and R-bands have become B and V effective bands. The K-correction for SN 2001gh was estimated by measuring the differences between synthetic photometry in the observed and rest-frame SN spectra. Since we had only two spectra of SN 2001gh and, consequently, we were not able to fully match the photometric coverage, we enhanced the K-correction spectral database by adding a set of spectra of nearby SNe Ib, artificially redshifted to the distance of SN 2001gh. A K-correction of the order of a few tenths of a magnitude was measured at all epochs. We also considered a Galacting reddening correction of $A_{V,G} = 0.07$, while the contribution of the host galaxy was assumed as negligible.

The photometric monitoring of SN 2001gh is rather sparse, but allows to well cover the SN evolution during the photospheric phase. The B and V light curves show a slow rise and unusually broad peaks if compared with those of normal type Ib SNe.

Fig. 1–(b) shows the V band absolute light curve of SN 2001gh (with an adopted distance modulus of 39.36 $\pm$ 0.10, as derived from the spectroscopy), and is compared with those of SNe 2005bf (peculiar Ib, [5]), 1999ex (Ib, [6]), 1993J (IIb, [7, 8]) and 1997ef (Ic, [9]). The light curves of two hydrogen-rich CC SNe showing broad and delayed light curve peaks are also shown, viz. the type II SNe 1987A [10] and 2000cb [11]. The maximum of SN 2001gh is brighter and broader than those of the other CC-SNe, with the exception of SN 2005bf, which shares some similarities with SN 2001gh. But its delayed peak, by $\sim$ 30 days, is roughly comparable with those of SNe 1987A and 2000cb. This is a probe of the compactness of the progenitor star. This peculiar behaviour in the light curve together with an anomalously slow spectral evolution make SN 2001gh an unprecedented event.

CONSTRAINING THE PROGENITOR OF SN 2001GH

The observables of SN 2001gh suggest that this object is peculiar compared with most H-deprived CC-SNe studied so far. In particular, both the high peak luminosity and the slow rise time to maximum would indicate high explosion energy, massive ejecta envelope and a larger amount of synthesized ^{56}Ni compared with normal type Ib/c SNe (e.g. [6]).

Then, the very slow spectral evolution exhibited by SN 2001gh is unprecedented. The second spectrum obtained one month after the first one is still dominated by He I lines, while in normal SNe IIb-Ib it evolves much faster, displaying metal lines already a few days after core-collapse (e.g. [3]). This is indicative of unusually high temperatures of the ejected material, which probably results from the particularly high explosion energy.

Taking into account all the properties of SN 2001gh described above, and in order to constrain the explosion parameters and the nature of the progenitor star, we propose three alternative explosion scenarios.

- From the modelling of the observables of SN 2001gh (using a semi-analytical code which reproduces simultaneously the bolometric light curve, the photospheric velocity and the continuum temperature evolutions of a CC-SN [12]), we find that the precursor of SN 2001gh was possibly a young, very massive Wolf-Rayet star, with its He envelope (almost) intact at the time of explosion. Main derived parameters from the model are E $\approx 6x10^{52}$ erg, $M_{Ni} \sim 0.5$ $M_\odot$, $M_{ejecta} \sim 30 M_\odot$ and initial radius $R_0 \approx 43$ $R_\odot$. The large ejected mass and explosion energy are consistent with an originally very massive precursor, with initial mass of at least 50 $M_\odot$, probably quite similar to (though less evolved than) those producing SN 2006jc and other type Ibn SNe (e.g. [13]). The large ejected mass of SN 2001gh is necessary to account for the broad luminosity peak, while a massive He envelope explains the unusually slow spectral evolution.
- SN 2001gh might also arise from the explosion of a relatively compact star ($R_0 \approx 4x10^{12}$ cm), with a kinetic energy of $\sim 18x10^{51}$ erg, ejecting about 15 $M_\odot$ of material (most of which is He) and 0.65 $M_\odot$ of ^{56}Ni (these parameters have been also derived from the semi-analytical code but considering other constrains – see [14] for more datials). In this case the explosion epoch is slightly later. Such a large M_{Ni} mass is infrequent in core-collapse SNe, but comparable with those observed in some broad-lined CC-SNe (e.g. SN 1998bw, [15]) or in particularly luminous type Ic events (e.g. SN 1999as, [16]).
- In both scenarios presented above, the models predict faster evolution of v_{ph}, which is not observed in the reality. If we add also some evidence of boxy profile in the He I lines in SN 2001gh spectra, a third interpretation could be offered, that we are seeing a more canonical SN Ib with a dense, He-rich circumstellar shell produced via pre-SN wind. The high peak luminosity of SN 2001gh would be explained through reprocessing of UV light in the shell, in analogy to that observed in some luminous type IIL SNe ([17]).

In any case, the (almost) unique properties of SN 2001gh are a clear indication that our current knowledge on mechanisms producing the variety of observables in CC SNe is still incomplete. SN 2001gh-like events are intrinsically rare, and their present rate

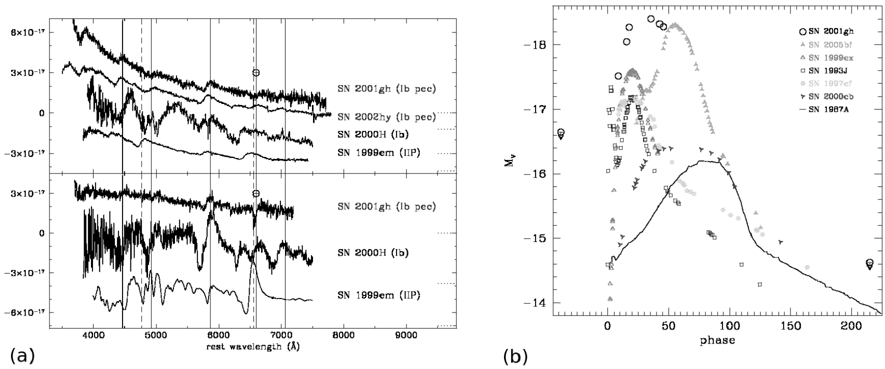

FIGURE 1. **(a)**: Comparison between optical spectra of SN 2001gh a few days before maximum light (*top*) and one month later (*bottom*) with those of SN 2002hy (peculiar, 2001gh-like SN Ib), SN 2000H (SN Ib, [3]), and SN 1999em (SN IIP, [4]). Vertical solid lines mark the position of the main He I features, while the dotted lines give the rest wavelength position of Hα and Hβ. The label $\oplus$ indicates the the strongest telluric band. All spectra have been reddening and redshift corrected. **(b)**: V-band absolute light curve for SN 2001gh compared with those of SNe 2005bf [5], 1999ex [6], 1993J [7, 8], 1997ef ([9]), 2000cb [11] and 1987A ([10]). All curves have been computed with the extinction and distance modulus values reported in the mentioned papers.

is between 0.002 (considering the rate of CC at $z < 0.017$, [18]) and 0.054 SNu [1] (considering the rate of CC at $\bar{z} = 0.2$, [2] ([14]).

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[1] 1SNu = 1SN $(100\ \mathrm{yr})^{-1}(10^{10} L_{\odot}^{B})^{-1}$