The Extreme LBV Star GR 290 (Romano’s Star) in M 33
Optical Spectrophotometric Monitoring

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ABSTRACT

We study the long term, S Dor–type variability and the present hot phase of the Luminous Blue Variable star GR 290 (Romano’s Star) in M 33 in order to investigate possible links between the LBV and WNL stages of very massive stars. We use intermediate resolution spectra, obtained with the William Herschel Telescope in December 2008, when GR 290 was at minimum (\(V \sim 18.6\)), as well as new low resolution spectra and \(B V R I\) photometry obtained with the Loiano and Cima Ekar telescopes during 2007–2010. We identify more than 80 emission lines in the 3100–10000 \(\text{Å}\) range covered by the WHT spectra, belonging to different species: the hydrogen Balmer and Paschen series, neutral and ionized helium, \(\text{C} \\text{iii}\), \(\text{N} \\text{ii}–\text{iii}\), \(\text{S} \\text{iv}\), \(\text{Si} \\text{iii}–\text{iv}\), and many forbidden lines of \([\text{N} \text{ii}]\), \([\text{O} \text{iii}]\), \([\text{S} \text{iii}]\), \([\text{A} \text{iii}]\), \([\text{Ne} \text{iii}]\), \([\text{Fe} \text{iii}]\). Many lines, especially the \(\text{He} \text{i}\) triplets, show a P Cygni profile with an \(a–e\) radial velocity difference from \(-300\) to \(-500\) \(\text{km s}^{-1}\).

The shape of the 4630–4713 \(\text{Å}\) emission blend and of other emission lines resembles that of WN9 stars; the blend deconvolution shows that the \(\text{He} \text{ii} 4686 \text{Å}\) has a strong broad component with \(\text{FWHM} \sim 1700\) \(\text{km s}^{-1}\). During 2003–2010 the star underwent large spectral variations, best seen in the 4630–4686 \(\text{Å}\) emission feature. Using the late–WN spectral types of Crowther & Smith (1997), GR 290 apparently varied between the WN11 and WN8–9 spectral types, the hotter being the star the fainter its visual magnitude. This spectrum–visual luminosity anticorrelation of GR 290 is reminiscent of the behaviour of the best studied LBVs, such as S Dor and AG Car. During the 2008 minimum we find a significant decrease in bolometric luminosity, which could be attributed to absorption by newly formed circumstellar matter. We suggest that, presently, the broad 4686 \(\text{Å}\) line and the optical continuum are formed in a central WR region, while the narrow emission line spectrum originate in an extended, slowly expanding envelope, that is composed by matter ejected during previous high luminosity phases, and ionized by the central nucleus. We argue that GR 290 could have just entered in a phase preceeding the transition from the LBV state to late WN type.

Subject headings: stars: evolution – stars: variable – S Dor stars: individual (GR 290) – stars: W–R – galaxies: individual (M 33)

1. Introduction

In a pioneer study of luminous stars in nearby galaxies, Humphreys & Davidson (1979), commenting on the evolution of the most massive stars in the Milky Way and the Large Magellanic Cloud, recognized that the distribution of the most luminous hot stars in the HR Diagram defines a locus

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of declining luminosity with decreasing temperature: the Humphreys–Davidson (HD) limit. Taking into account the tight upper luminosity limit observed for the yellow and red supergiants at log($L/L_\odot$) \textgreater 5.8, these authors suggested that the most massive stars ($M \geq 60 M_\odot$) do not evolve to cooler temperatures, as do stars of intermediate and low mass. Episodes of high mass loss, like the ones observed in $\eta$ Car, P Cyg, S Dor and the Hubble–Sandages variables in M 31 and M 33, would be responsible for this behaviour. To define this group of unstable, evolved hot stars in the upper H–R Diagram, Conti (1984) introduced the term Luminous Blue Variables (LBVs). Later, Humphreys & Davidson (1994) distinguished between normal LBV variability cycles and giant eruptions. They defined normal those cycles in which changes of up to 1–2 magnitudes are observed in the visual band at more or less constant bolometric luminosity, on timescales of years to decades. These are the so–called S Dor variability phases, named from the prototype of the class in the Large Magellanic Cloud (van Genderen 1979, 2001). In a few cases changes of 3 magnitudes or more in the visual band have been recorded, like the ones observed for $\eta$ Car in the 19th century and P Cyg in the 17th century, the so–called giant eruptions (Humphreys & Davidson 1994).

Since 2003, we have been carrying on an extensive monitoring of LBVs in M 33 (Viotti et al. 2006), mostly based on observations at the Italian Loiano and Cima Ekar Observatories, with the aim of investigating the physical nature and evolutionary status of variable stars in the upper H–R Diagram and the origin of their instabilities. Among the objects of our study, the Romano’s Star (GR 290), is the most interesting, both for its high temperature and luminosity, and for the large optical variations (Romano 1978, Sharov 1990, Kurtev et al. 2001; Sholukhova et al. 2002; Polcaro et al. 2003; Viotti et al. 2006; Marveva & Abolmasov 2010). GR 290 is an LBV placed at about 4.2 kpc to the North-East of the center of M 33, near the young OB association OB 89. Its historical light curve is characterized by ample, long–term variations between 16.2 and 18.2 in the $B$–band (e.g., Romand 1978; Sharov 1990; Kurtev et al. 2001; Sholukhova et al. 2002). Recently, GR 290 reached a deep minimum followed by the appearance of a very hot spectrum, the hottest so far recorded for an LBV (Viotti et al. 2007). In this paper, we present new spectroscopic and photometric observations of GR 290 collected during the present hot state. In § 2 we summarize the new observations and the procedures of data analysis. In § 3 we describe the intermediate resolution spectrum obtained with WHT in December 2008, and analyze the spectral variations observed during 2003–2010. In § 4 we discuss our results, with some final considerations in § 5.

2. Observations

This work is based on photometric and spectroscopic observations of GR 290, performed with several telescopes between 2003 and 2010. The observational data taken between February 2003 and December 2006 have been already discussed in our previous papers (Polcaro et al. 2003, Viotti et al. 2006, Viotti et al. 2007). New low resolution spectra have been obtained in January 2007, January–February 2008, September 2008, February 2009 and January 2010 with the Loiano telescope. All these spectra, taken with the broad wavelength range grism–4 instrumental setup, have a dispersion of \textasciitilde 4 Å per pixel. In addition, new $B V R I$ images were obtained. The observations are reported in Table 1, where the magnitudes are the mean of two or more individual observations and the errors in brackets are standard deviations of the fits. The $B V R I$ magnitudes are derived as described in our previous papers. In Fig. 1 we plot all our $B V R$ measurements during 2003–2010.

Intermediate resolution spectra of GR 290 have been obtained on 2008 December 4 with the ISIS spectrograph mounted at the 4.2 m William Herschel telescope (WHT) of the Isaac Newton Group of Telescopes. The R300B and R158R gratings mounted on the blue and red arms, respectively, provide corresponding nominal dispersions of 0.86 Å/pixel and 1.81 Å/pixel. Two exposures for each wavelength range were obtained with a S/N for the continuum of about 30 and 40 near 4200 Å and 6500 Å for the blue and red spectra, respectively. All the spectra were analyzed using the standard IRAF procedure\textsuperscript{1}. Multi–Gaussian fits were used to analyze line blends and P Cygni pro-

\textsuperscript{1}IRAF is distributed by the NOAO, which is operated by AURA under contract with NSF.
files. We have also made use of a blue spectrum of GR 290 obtained in September 2006 at the WIYN 3.5 m telescope with a dispersion of 0.53 Å/pixel (see Massey et al. 2007), kindly provided to us by Philip Massey.

3. The spectrum of GR 290

3.1. The December 2008 spectrum

The December 2008 spectrum of GR 290 is shown in Figure 2 (a-i). For the line identifications, we have made use of the rich literature on the spectra of emission line stars, including WNL, symbiotic and B–emission stars, and the NIST database

\[ \text{http://physics.nist.gov/asd3} \] The observed wavelength and \( W_{eq} \) values listed in the table are averages (when available) on the two spectra for each wavelength range.

Neutral helium is the atomic species most abundantly represented in the spectrum of GR 290. As can be seen from Fig. 2, all the triplet and several singlet transition \( \text{He} \) lines show a component in absorption with a velocity separation between the absorption and emission components from about \(-300 \) km s\(^{-1}\) to \(-500 \) km s\(^{-1}\). Particularly evident is the P Cygni profile in the 3187 and 3888 Å lines originated from the metastable level \( 2^3S \) (Fig. 2a-b).

Near the strong 5015 Å \( \text{He} \) 1 line, about 11 Å to the blue side, is visible an intense emission line (Fig. 2f). The profile of the blend is similar to that observed in September 2006 by Massey et al. (2007) (bottom dotted spectrum in the figure), and by Crowther & Smith (1997) in the WN9–11 stars of the LMC, where it is commonly attributed to a blend of \( \text{N} \) II lines of multiplets 19 and 22 (marked by vertical bars in the figure). These lines have been observed in emission in the spectrum of late O stars, as well as in some Be stars, and have been attributed to selective excitation of the upper \( 3d^2 \text{P}^0 \) and \( 3d^2 \text{F}^0 \) levels (Walborn & Howarth 2000, Walborn 2001). However, the line is narrower than expected if it were a blend of many lines in the range 4987–5007 Å. In addition, the observed wavelength of the emission at about 5003 Å is also compatible with that of the \([\text{O} \ iii] 5006.8\) Å nebular line, taking into account the stellar radial velocity. This, together with the presence of a weak emission near 4955 Å which could correspond to the weakest 4959 Å component of the \([\text{O} \ iii] \) doublet, seems rather to favour the identification of the 5003 Å emission with \([\text{O} \ iii] \). The observed 5007/4959 intensity ratio of 4.3±2.0 is not in disagreement with the theoretical ratio of the \([\text{O} \ iii] \) doublet, although we think that both the \( \text{N} \) II blend and the \([\text{O} \ iii] \) line do contribute by a comparable intensity to the 5003 Å feature. Note that an emission is present around the expected wavelength of the auroral 7319 Å transition of \([\text{O} \ ii] \). The presence of the \([\text{O} \ iii] \) doublet emission lines during minimum has been recently confirmed by the higher resolution observations described by Maryeva & Abolmasov (2010). The \([\text{O} \ iii] \) doublet has also been seen strong in emission in the spectrum of B416, another LBV in M 33 (Fabrika et al. 2005).

The 4686 Å Paschen–α line of ionized helium appears as a very strong symmetric emission with a peak intensity about one third of that of Hβ. This line, that is part of the broad 4600–4700 Å blend, the so–called \( f \)–feature, will be discussed more in details in § 3.2. Also the Paschen–β \( \text{He} \) \( \Pi \) line at 3203 Å is observed in emission, although not so prominently over the continuum. An absorption line near 4536 Å is present in both the WHT blue spectra, as well as in the WIYN spectrum of September 2006 (Fig. 4d). This line can be identified with the Brackett–c \( \text{He} \) \( \Pi \) 4541 Å line, slightly blue shifted with respect to the emission line rest frame.

The Balmer and Paschen series lines of hydrogen are seen in emission up to H12 and P14 at our resolution. The flux minimum in between the Si \( iv \) 4089 Å emission and the 4100 Å Hδ+N \( \text{iii} \) blend, that falls below the continuum level (Fig. 2c), has to be attributed to a P Cygni absorption component of Hδ, with a possible contribution of the \( \text{N} \) \( iii \) 4097 Å line. The steeper blue side of Hδ and Hγ also suggests the presence of an unresolved weak P Cygni component (Figs. 2d, 2f). The near–infrared region is noisy and does not allow to resolve the profile of

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2 Ralchenko, Yu., Kramida, A.E., Reader, J. and NIST ASD Team (2008). NIST Atomic Spectra Database (version 3.1.5), [Online]. Available: \[http://physics.nist.gov/asd3\] (2009, September 3). National Institute of Standards and Technology, Gaithersburg, MD

3 Table 2 is published in its entirely in the electronic edition of the \textit{Astronomical Journal}.
the Paschen lines (e.g., Fig. 2i).

In addition to N \textsc{iii}, singly ionized nitrogen is also present with several lines, most of which are thought to be selectively excited (see Walborn 2001). C \textsc{iii} is present with a weak emission line at 5695 \AA\ and with the blue triplet at 4647–50–51 \AA\ with a weak peak in between the N \textsc{iii} 4641 \AA\ and the [Fe \textsc{iii}] 4658 \AA\ emission lines (see also § 3.2). Si \textsc{iv} is present with the UV (RMT 2) and blue (RMT 1) multiplets that have the 2P\(^{o}\) level in common. Two emission lines at 4482 and 4501 \AA\ (Fig. 2d) have been identified with the S \textsc{iv} recombination lines 4485.662 \AA\ and 4504.093 \AA\ belonging to the high excitation \(2s^24d^2D - 3s^24f^2F\) transition. These lines have been frequently observed in the spectra of O–type stars, and have been first identified by Werner & Rauch (2001). As discussed by these authors (see also Morrell et al. 1991), the presence of these lines might be an indication of the high intrinsic luminosity of GR 290.

In addition to [O \textsc{iii}] discussed above, the spectrum of GR 290 displays forbidden lines of doubly ionized sulfur (e.g., 3797 \AA, 6312 \AA, 9532 \AA), argon (7136 \AA, 7751 \AA), neon (3869 \AA), and iron (3240 \AA, 5270 \AA), as well as the yellow and red lines of [N \textsc{ii}]. These lines are not unusual in the spectrum of luminous emission line stars, including AG Car during its hot minimum, P Cyg and η Car. In the case of GR 290, they probably arise from the compact elongated (6–8 arcsec in the NS direction) circumstellar nebula observed by Fabrika et al. (2005) in Hβ, which has an expansion velocity of a few 10 km s\(^{-1}\) in the observer’s direction. The absence of [S \textsc{ii}] and [Fe \textsc{ii}] in GR 290 is in agreement with its present higher ionization level than in the other LBVs.

3.2. The 4650 \AA\ emission blend

Of particular interest is the strong 4640–4700 \AA\ emission feature that is a blend of emission lines belonging to many different species including of N \textsc{ii}, N \textsc{iii}, C \textsc{iii}, [Fe \textsc{iii}] and He \textsc{ii} (Fig. 3). We have tentatively fitted the 4620–4713 \AA\ spectral region with a combination of the following lines: N \textsc{ii} 4621.39–30.54, N \textsc{iii} 4634.14–40.64–41.85, C \textsc{iii} 4647.42–50.25–51.47, [Fe \textsc{iii}] 4658.05–67.01, He \textsc{ii} 4685.08, [Fe \textsc{iii}] 4701.53, and He \textsc{i} 4713.15. For all the lines we have assumed the same FWHM of 6.2 \AA, uncorrected for spectral resolution. A P Cygni profile has been used for the He \textsc{i} 4713 \AA\ line assuming for the absorption and emission components a radial velocity difference of \(\sim 220\) km s\(^{-1}\). However, the fit does not fully account for the flux level around 4670 and 4690 \AA. We attribute this excess to the presence of broad wings of the He \textsc{ii} 4686 \AA\ line. This is better seen in the lower panel of Fig. 3, where we show the spectral region after subtraction of the contribution of all the above emission lines except He \textsc{ii} 4686 \AA. The residual is fitted by two Gaussians with FWHM=6.2 \AA\ and 26.5 \AA\ for the narrow and broad components, respectively. The width of the latter component corresponds to a Doppler broadening of \(\sim 1000\) km s\(^{-1}\). The derived broad/narrow flux ratio is equal to 1.4. We cannot exclude a minor contribution to the 4650 \AA\ blend of other weaker lines, such as the C \textsc{iv} 4658 \AA\ line, although the absence of the strong C \textsc{iv} doublet at 5801–12 \AA\ would argue against its presence in the 4650 \AA\ blend. The final fit is shown in the top panel of Fig. 3. In the fit the blue tail of the 4650 \AA\ blend is attributed to N \textsc{ii}. But it could be more likely attributed to a broad component of the N \textsc{iii} 4634–42 \AA\ triplet. If this is the case, we estimate that its strength should be 30–50 % of the 4686 \AA\ broad component. Broad emissions could be present in other spectral regions, but the small contrast with the continuum and, in many cases, the blending of lines do not allow to perform the same analysis as for the He \textsc{ii} 4686 \AA\ line.

Such a double profile, with narrow and broader emission components, has been observed in the Ofpe/WN9–WN10h star R99 in LMC (Crowther & Smith 1997). In that case the broad component is red shifted with a FWHM of 600 km s\(^{-1}\). We also recall that STIS/HST observations of η Car, which have allowed to resolve and study the spectrum of the central source (0.1 arcsec), show that the central source has mainly broad (FWHM \(\approx 850\) km s\(^{-1}\)) permitted emission lines, while the strong narrow emission lines observed in the ground based spectra are formed in the circumstellar nebula (Hillier et al. 2001). It is therefore likely that a similar scenario might account for the double components which we find here for GR 290, with a broad–line, high temperature spectrum formed in an unresolved central source, and narrower emission lines originating in a circum-
stellar, slowly expanding nebula ionized by the UV radiation of the central source.

3.3. Spectral variations

The spectrum of GR 290 is generally characterized by prominent hydrogen and neutral helium emission lines, and by the 4630–4700 Å emission blend, which is a feature typical of Of and WN–type stars. These lines have shown during the years some variability, with the 4630–4700 Å emission blend varying the most. To illustrate this we have plotted in Fig. 4 the 4400–5100 Å spectral range of GR 290 as it appeared in various observations taken during 2003-2010. The spectrum of the Of/WN9 star UIT 3 in M 33 is also shown for comparison. In the picture, the spectra of GR 290 taken at WIYN in September 2006 and at WHT in December 2008 have been degraded to the Loiano spectral resolution. The Cima Ekar spectra of GR 290 of February and December 2004, and of UIT 3 have a slightly lower spectral resolution than those taken with the Loiano telescope, so that the 4630–4660 Å feature, the He ii 4686 Å and the He i 4713 Å lines are poorly resolved. The Loiano January 2005 spectrum was obtained with the higher resolution grism 7. From this comparison we can see that, in correspondence with the 2006 minimum, the 4630–4700 Å blend has become prominent and has stayed so since, with maximum strength in the January–February 2008 spectra. During 2003–2010 the strength of the hydrogen and neutral helium emission lines also varied, although to a lesser extent. These variations are summarized in Table 3 which gives the equivalent widths of the 4630–4700 Å blend, and of the He ii 4686 Å, He i 5876 Å and Hα emission lines, with an estimated error of 10% for Hα and the 4650 Å blend, and 20% for the two helium lines. The equivalent width of the 4686 Å broad+narrow line has been derived by fitting the 4630–4713 Å blend in the low resolution spectrograms with a combination of Gaussians as described above in § 3.2. From Table 3 one can see that, after February 2003, the equivalent width of He ii 4686 Å has dramatically decreased till a minimum value in 2004–2005. At this epoch, this line was not distinguishable, at the resolution of our spectra, while the whole 4630-4700 Å blend reached a deep minimum. It is possible that, during this phase, the N ii was the dominant contributor to the blend (see Polcaro et al. 2003), as it has been the case for the spectrum of AG Car during its Of/WN9 phase (e.g. Viotti et al. 1993, Smith et al. 1994). Unlike the trend shown by the 4650 Å blend, the relative strength of Hα between the beginning of 2004 and 2005 displayed only a slight increase, up to an $W_{eq}$ of 130 Å, and remained around this value in the following years. As for the He i 5876 Å emission line its $W_{eq}$ reached a maximum by the end of 2006, followed by a slight decrease in the following years.

During mid 2006 up to January 2010 GR 290 has exhibited a spectrum very similar to that of late WN stars. Therefore in order to provide a spectral class to GR 290 during its different phases we have used the classification scheme for WNL stars proposed by Crowther & Smith (1997). The strength of the N iii 4634–4641 Å, He ii 4686 Å emissions relative to the He i lines suggests that at minimum the star belonged to the WN9 subtype, while before 2006, when the star was brighter, it could be classified WN10–11. The spectral type variations of GR 290 can also be analyzed considering the intensity of the He ii 4686 Å and He i 5876 Å lines by plotting them in a $W_{eq}$ (5876) v/s $W_{eq}$ (4686) diagram used for classifying WNL stars (Crowther & Smith, 1997). In this diagram, shown in Fig. 5, the areas identifying the WN and Of spectral types are marked and labelled. According to this classification scheme, GR 290 has changed spectral subtype from WN9 in 2003 to WN11 in 2004-2005, and again to WN9 since 2006. At the beginning of 2008 the star reached its hottest state, with the He ii 4686 Å line as strong as in the LMC and galactic WN8 stars (Fig. 5). However, in our low resolution spectra of January–February 2008, there is no evidence for the presence in particular of a prominent N iv 4067 Å emission line which should be present, according e.g. to Crowther & Smith (1997), in a spectrum of WN8 subtype, nor this line has been identified in the high resolution spectrum of January 2008 discussed by Maryeva & Abolmasov (2010).

Both the WIYN September 2006 and the WHT December 2008 mid resolution spectra of GR 290 agree qualitatively well with that of the WN9h star BE 381 in the LMC (shown by Crowther & Smith, 1997), but the emission line spectrum is definitely stronger in GR 290. We suggest that this effect is associated with its intrinsic luminosity, higher
than that of the LMC and galactic WN9 stars. We argue that this luminosity effect can explain the 2008 position of GR 290 in the WN8 region in the diagram of Crowther & Smith (1997). Hence, a WN9h+ subtype seems more appropriate to that epoch, where the plus sign is used in order to indicate stronger than normal emission lines for a WN9h spectral type.

4. Discussion

4.1. The light curve

GR 290 has been monitored photometrically for almost 50 years. The historical light curve is shown in Fig. 6. Since 1960 GR 290 displayed luminosity minima in 1960–1962, 1977, 2001 and, probably, in 1986, all with about the same $B \sim 18.0$. Light maxima were recorded in 1967–75 and, probably, in 1980–85, both with $B$ around 17.2, and, the strongest one, in 1993–94 with $B_{\text{max}} = 16.2$. The recent light curve is illustrated in Fig. 1. Between February 2003 and December 2004–February 2005 the star’s luminosity gradually increased by about half a magnitude up to a maximum near 2005.0 with $B \simeq 17.1$. This was about one mag fainter than in the 1993 maximum, but comparable to the two previous maxima. In November 2006, a marked luminosity decrease was recorded in all bands, with a magnitude jump of about +1.3 in all colors. Since then the star has remained at minimum with small photometric variations. Mid infrared observations of GR 290 with the SPITZER satellite, reported by McQuinn et al. (2007), showed a trend similar to that of the optical bands, with a slight increase in the 3.6 $\mu$m and 4.5 $\mu$m bands between January 2004 and January 2005, followed in August 2005 by a large flux decrease of +0.6 mag in both bands. A flux decrease in the blue by the end of 2005 was also recorded by Maryeva & Abolmasov (2010). These observations suggest that the star’s fading has started in 2005. Since, according to Massey et al. (2007) and to Maryeva & Abolmasov (2010), in August–September 2006 the spectrum of GR 290 already displayed a prominent 4650 Å emission blend similar to the present one, we argue that at that date the decrease to minimum had already completed. Hence, the star must have faded at a rate of at least $+0.10$ mag per month, apparently faster than the previous fading phases (e.g. Sholukhova et al. 2002).

The large photometric variation of 2006 was accompanied by a profound spectroscopic evolution, which is illustrated in Fig. 4 and quantified in Table 3. There is a clear opposite trend between the visual brightness and the equivalent widths of the 4630–4700 Å blend and of the He II 4686 Å line. This is best illustrated in Fig. 7 where the equivalent width of these high temperature features is plotted against the visual magnitude. The hot phase corresponds to the $W_{\text{eq}}$ value of $\sim 40$ Å for the 4630–4700 Å blend, when the visual magnitude was about 18.5 with small photometric variations. The single He II 4686 Å line contributed then $\approx 40\%$ to the blend. This blend became about four times weaker during the high luminosity ($V \sim 17.2–17.7$) phase. This plot seems to suggest a physical correlation between $W_{\text{eq}}$ and $V$, although the lack of observations at intermediate visual magnitudes prevents a quantitative evaluation. As for the Hα and He i 5876 Å emission lines, both appear to have slightly strengthened during the low luminosity phase, but this increase seems to be less correlated with the visual magnitude of the star.

Two spectra of GR 290 taken in September 1998 and July 1999 at the 6 m BTA telescope during the descending luminosity phase, are described by Fabrika et al. (2005). These authors identified prominent Balmer and He i emission lines without significant emission in the 4650 Å blend. At that epoch, the star had a luminosity of about $B \sim 17–17.6$ (see Sholukhova et al. 2002). According to Szeifert (1996), a spectrum taken in October 1992 near the strong 1992 maximum ($B \sim 16.2$), showed, in addition to prominent Hα, faint He i and a few metal lines (see also top of Fig. 1 in Fabrika 2000). This led Szeifert to suggest a late-B spectral type for GR 290 in 1992. These earlier observations confirm and extend the above discussed visual luminosity–spectrum counter trend.

It is known that in the LBVs, when they undergo ample, long-term photometric S Dor type variations, the fading in the visual is accompanied by an increase of the excitation temperature of the emission line spectrum and, in some cases, by the blueing of the color index. The spectrum-visual luminosity anti-correlation observed in GR 290 is reminiscent of the behaviour of the best studied LBVs, such as S Dor and R127 in LMC, and the
galactic object AG Car. In this regard, GR 290 is peculiar for the excitation temperature reached during its minimum phase, one of the highest ever observed in an LBV, if we exclude the explosive, LBV–like behaviour of one stellar component of the massive close binary system HD 5980. This star seems to have displayed a WNE spectrum during the long lasting phase, prior to the 1993–94 outbursts, when its spectrum became WN11-B1.5 (Koenigsberger 2004, Koenigsberger et al. 2010). No significant blueing of the color index of GR 290 was observed, but this could be attributed to the fact that during our period of observations, the star always displayed a peculiar hot spectrum with an energy distribution likely far from that of normal early type stars. Although, admittedly, our color index measurements can be inaccurate for such a faint object.

4.2. How luminous is GR 290?

In order to put GR 290 in the context of the other known LBVs it is necessary to estimate the star’s luminosity in its various phases. The black–body fit of the optical–near infrared energy distribution of GR 290 in December 2004, when the star had V=17.2 and a WN11–type spectrum, provides a black–body temperature between 20 000 and 30 000 K (Viotti et al. 2006). The large range is due to the uncertainty on the adopted color excess, respectively $E_{B-V} = 0.16$ (the average of the nearby associations OB 88 and OB 89) and $E_{B-V} = 0.22$ (assuming for the unreddened $U-B$ and $B-V$ the color indices as for late–O stars). Crowther & Smith (1997), from the analysis of the late WN stars in the LMC, derived for the WN11 spectral type an effective temperature of 25 000–27 000 K and a bolometric correction around $-2.8$. Groh et al. (2009) derived $T_{eff}=22 800$ K and $BC=-2.5$ for the galactic LBV AG Car during its 1985–1990 visual minimum, when the star exhibited a WN11–type spectrum. If we adopt for the December 2004 spectrum of GR 290 the bolometric correction of AG Car during its WN11 phase and the same color excess $E_{B-V}=0.16$ of the nearby OB associations, we derive $M_{bol}=-10.6$, or $L_{bol}=1.4\times10^6\,L_\odot$, with an assumed distance modulus for M 33 of 24.8 (from Kim et al. 2002).

Then, if we assume for GR 290 $T_{eff}=22 800$ K, we derive an effective radius $R_{eff}\simeq76\,R_\odot$.

At the February 2008 deep minimum the star was about 1.5 mag fainter in V than in December 2004, while its spectrum was intermediate between WN9 and WN8. Assuming for this phase a bolometric correction of $-3.0/-3.3$ (e.g., Nugis & Lamers 2000), and the same $E_{B-V}$ as above, we obtain $M_{bol}\simeq-9.8$, or $L_{bol}\simeq0.66\times10^6\,L_\odot$, therefore a bolometric luminosity which is about half than in December 2004. Taking an effective temperature suitable for WN9 stars, $\sim28 000$ K, we obtain an effective radius of $\sim35\,R_\odot$.

At the highest maximum of 1993 GR 290 was $0.9$ mag brighter in $B$ than in December 2004. According to Szeifert (1996) the line excitation was much lower, probably similar to that of AG Car during rise to a visual maximum. If we assume a visual bolometric correction of $-1.2$, similar to that derived by Groh et al. (2009) for AG Car near maximum, and a reddening corrected $B-V$ color index close to zero, a bolometric magnitude around $-10.5$ is obtained, close that of December 2004. The corresponding effective radius is as large as about $190\,R_\odot$ for a $T_{eff}$ value of $14 000$ K. Of course, one should keep in mind that the value of $M_{bol}$ obtained for 1993 is quite uncertain, mostly due to the large uncertainty on the adopted $BC$, and we cannot exclude a 1993 luminosity much different from that of December 2004.

If we follow what is generally known for LBV behaviour, in GR 290 the counter trend of the visual luminosity and of the emission line excitation would suggest a variation with more or less constant bolometric luminosity, similarly to what has been inferred for the S Dor variation of AG Car (e.g. Viotti et al. 1984, Lamers et al. 1989, Leitherer et al. 1994). However, if we consider the energy distribution of GR 290 at the minimum visual luminosity of 2008, it is not so easy to justify how the bolometric luminosity might have remained constant since December 2004. Of course, our luminosity estimates critically depend on the assumed values of the bolometric corrections. According to the proposed model atmospheres as also discussed above, the range of the uncertainty on the $BC$ difference between the two epochs is likely to be around $\pm0.3$ magnitudes. However, even taking this uncertainty into account, the luminosity difference of about a factor two cannot be attributed to a change of the energy distribution at constant luminosity alone, since it would imply an unlikely, too negative bolometric correction for
the FeII broad wing, which is not seen in the prominent hydrogen lines. The HeII broad wing is not seen in the prominent hydrogen lines. The presence of a high velocity (∼0.8 mag extinction of the visual light, additional to the interstellar one. In this hypothesis, the light from GR 290, in February 2008, is partly absorbed by a circumstellar opaque envelope formed following the 2004–2005 light maximum, fed by matter ejected by the star.

It would be interesting to find out whether this apparent luminosity decrease is associated with an increase of the mid-infrared flux.

We finally remark that, although it is difficult to interpret in the light of current models a change in $L_{bol}$ during S Dor variations for LBV stars, other authors have made similar suggestions e.g. for S Dor (van Genderen et al. 1997), AG Car (Groh et al. 2009) and AFGL2298 (Clark et al. 2009). According to Groh et al. (2009) this result for AG Car would imply the presence of physical mechanisms of conversion of the stellar radiative power into mechanical power to expand the outer layers. Previously, a similar mechanism was proposed by Andriesse, Donn & Viotti (1978) for η Car to relate a +1 mag decrease in bolometric luminosity since 1840 to the excess of mechanical power needed to drive its massive stellar wind.

In the case of GR 290, however, so far there are no independent evidences, such as a very high mass loss rate, that such a mechanism is at work after its 2005 maximum. Whether the intrinsic luminosity of GR 290 has changed during its S Dor variations is a point which will require further analysis.

4.3. The emitting envelope

We have seen that, in addition to the narrow HeI emission lines with a P Cygni profile, broad and narrow components are present in the HeII 4686 Å line with comparable strength. The broad component has been identified in the mid resolution spectrum of GR 290 obtained in December 2008, during the low luminosity phase of the star.

Similar broad wings are not seen in the prominent hydrogen lines. The HeII broad component indicates the presence of a high velocity (∼1000 km s$^{-1}$) region, hotter than the region producing the narrow emission line spectrum. As for the latter, the present day narrow line spectrum mimics fairly well the spectrum of a WN9 star, with a wide ionization range and a low expansion velocity (of a few 100 km s$^{-1}$).

The presence of two - high and low velocity - spectral components might be explained by line formation in a bimodal stellar wind, with the broad HeII component generated in a fast, hot polar flow, and the narrow lines in an equatorial, denser and cooler one. Such bimodal winds have been invoked to explain similar observations in other LBVs. A wind asymmetry could also be suggested by the asymmetric shape of the circumstellar nebula observed by Fabrika et al. (2005).

Anyhow, the actual spatial structure of the nebula requires a better assessment with higher resolution observations, as its shape might provide information about the past history of the star. We instead suggest that the hot region could be identified with the central stellar nucleus of GR 290 with a dense high velocity wind, similar to that of Wolf–Rayet stars, surrounded by a cooler shell which is expanding with a low velocity. This shell, fed by the stellar wind, would have higher optical thickness during the high luminosity phases. The continuum therefore forms in the envelope at different apparent radii in different luminosity phases. During the minimum phases, the envelope opacity would become lower and the spectrum of the underlying nucleus emerges. At this time the measured radius would correspond to the WR–type envelope of the central nucleus. Other broad emission lines in addition to that of HeII 4686 Å that should be formed in the central nucleus, could be masked by the rich narrow emission line spectrum. This point will be analyzed with new higher quality spectra.

4.4. Evolutionary considerations

The very high luminosity of GR 290 places the star in the upper H-R Diagram near the most luminous early–type stars. Presently GR 290 has many spectral characteristics in common with the late WN stars displaying hydrogen lines, except for the large spectrophotometric variability. In the evolutionary sequence of very massive stars the position of stars with a spectrum similar to late WN–type and with hydrogen in their spectra, the so–called WNH stars (Smith & Conti 2008), is still under debate. They may be in an early evolutionary phase of core He burning with an H envelope not yet completely dissipated. In this scenario, the WNH phase occurs immediately after, or instead of, the LBV phase. Another school of thought puts at least the most luminous WNH stars (log
\( L/L_\odot \) above 5.8–6.0) before the LBV phase, so in a core H burning stage, evolving directly from the main sequence to the Wolf-Rayet stage perhaps even without an intermediate LBV phase. The masses of such WNH stars seem to be statistically higher than genuine hydrogen–free Wolf–Rayet stars (Smith & Conti 2008), and this may indicate that they are much less evolved objects. The following LBV phase is then consequence of their high luminosity with mass loss rates determined by the Eddington luminosity limit being exceeded. GR 290 has a luminosity around \( 10^6 L_\odot \), therefore of the same order as expected for the very luminous WNH stars, except that displays large long term photometric variations typical of LBVs, while WNH stars do not. An evolutionary development has been suggested in the literature with very massive stars with initial mass larger than \( \sim 40 M_\odot \) displaying LBV activity very early in their evolution, perhaps even while in core H burning. During this stage the stars would still be very luminous and display a variable WN9–11 spectrum while undergoing the LBV transient hot phases, as indeed observed for GR 290, before progressing on to WN8 stars (see Smith et al. 1994, Crowther et al. 1995, Crowther & Smith 1997). GR 290 is a typical LBV for its large spectrophotometric variations and, presently, it is in a state, rather extreme for an LBV, contiguous to the location of the WN8 stars. Additionally, from the spectrophotometric behaviour observed in recent years, we cannot exclude that the star is going through a transition phase, perhaps developing after some time the expected WN8 spectrum.

5. Conclusions

We have used recent spectrophotometric data together with existing literature data to study the long–term behaviour of the LBV star GR 290. The star is peculiar because of the high excitation temperature at minimum, higher than ever observed in a confirmed LBV. We find that one cannot easily account for the observed spectral and luminosity changes without assuming that the bolometric luminosity has significantly changed during the present minimum phase, in contrast with what is generally believed in the case of LBVs. There are few other LBV objects with such behaviour, which, as discussed above, can be attributed to conversion of radiative power into mechanical power. We advance the alternative hypothesis that the luminosity decrease may only be apparent and be due to an increase in circumstellar extinction. We also explore the possibility that, because of its very high luminosity and as indicated by its extreme spectrum, the star now is not too far to end this phase and to enter a late WN type star. This is of course only a hypothesis that in particular awaits further tests on surface chemical abundances, in order to determine the stars actual evolutionary stage.

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Fig. 2.— 2008 spectrum of GR 290 with some line identification. Two exposures are shown for each spectral region, with a vertical offset of $-0.2$ for the less exposed one (in red), to aid with assessing the presence of the various spectral features. In panels e–f the WIYN spectrum of September 2006 is also shown (dots) with a vertical offset of $-0.4$. Some lines of interest are identified in the figure. The vertical scale represents fluxes normalized to the continuum. The wavelength scales of the spectra have been shifted to fit the laboratory values.
Table 1: New photometry of GR 290.

| date              | B     | V     | R     | I     | telescope |
|-------------------|-------|-------|-------|-------|-----------|
| 2007 Jan. 28      | 18.48(0.05) | 18.57(0.05) | 18.42(0.04) |       | Loiano    |
| 2008 Feb. 07      | 18.52(0.07) | 18.62(0.04) | 18.41(0.09) |       | Loiano    |
| 2008 Sep. 08      |       | 18.2(1) |       |       | Loiano    |
| 2008 Dec. 06      | 18.2(2) | 18.6(2) | 18.2(2) |       | Cima Ekar |
| 2009 Feb. 09      | 18.45(0.11) | 18.36(0.04) | 18.27(0.05) | 18.40(0.09) | Loiano    |
| 2009 Oct. 26      | 18.33(0.06) | 18.33(0.04) | 18.16(0.03) |       | Loiano    |
| 2010 Jan. 21      | 18.33(0.06) | 18.38(0.05) | 18.14(0.03) |       | Loiano    |

Fig. 1.— The recent light curve of GR 290 from February 2003 to January 2010 in the $B$, $V$ and $R$ bands. For clarity, the different curves have been vertically shifted. As indicated by arrows next to $B$ $V$ $R$ labels in the plot, one reads the $B$ magnitudes in the upper part of the left scale and the $R$ magnitudes in the lower part, while the right scale refers to the $V$ magnitudes.

Fig. 3.— Upper panel: The 4620–4713 Å spectral range, as observed in December 2008, fitted (dashed line) by a combination of selected emission lines (marked by vertical bars and identified in the picture). The wavelength scale of the spectrum has been shifted to fit the laboratory wavelength. Both broad and narrow components have been included for the He ii 4686 Å line (see lower panel). For the He i 4713 line a violet-shifted absorption component has been included in the fit. Lower panel: Spectral residual distribution around the He ii 4686 Å line, after subtraction of the contribution of all the selected lines except He ii, fitted (dashed line) by narrow and broad Gaussian profiles (dotted lines).
Table 2
The December 2008 WHT spectrum of GR 290.

| \( \lambda^a \) | \( W_{eq}^b \) | ident. | remarks$^c$ |
|-----------------|-------------|--------|-------------|
| 3147            | -1.9:       | Si iv 94.56 |
| 3161            | -2.6:       | Si iv 65.72 |
| 3181.0a         | 1.4 He i 87.74 | PC |
| 3185.1          | -1.9 He i 87.74 |
| 3200.8          | -0.7 He ii 03.04 |
| 3238.8          | -1.1 [Fe iii] 39.74 |
| 3326.7          | -0.8 N iii 29.49 | bl N iii 30.11 |
| 3335.8a         | 0.2 N iii 42.78 | PC |
| 3341.9          | -0.6 N iii 42.78 |
| 3348.5a         | 0.3 N iii 54.33 | PC |
| 3353.7          | -0.7 N iii 54.33 |
| 3359.1a         | 0.3 N iii 67.25 | PC |
| 3366.8          | -1.8 N iii 67.25 | bl 3374 |
| 3382.2a         | 0.49 He i 87.25 | PC |
| 3385.3          | -0.41 He i 87.25 |
| 3627.8a         | 0.6 He i 34.23 | PC |
| 3632.6          | -1.1 He i 34.23 |
| 3697.7a         | 0.3 He i 05.00 | PC |
| 3703.9          | -0.6 He i 05.00 |
| 3748.7          | -1.1 H12 50.15 | ct N iii 52.63 |
| 3758.6          | -0.7 N iii 62.60 | weak |
| 3768.6          | -1.4 H11 70.63 | ct N iii 3771 |
| 3795.3          | -1.0 [S iii] 96.7 |
| 3801.9          | -0.6 Si iii 06.56 |
| 3812.6a         | 0.85 He i 19.61 | PC |
| 3818.1          | -1.1 He i 19.61 |
| 3833.0          | -2.1 H9 35.39 |
| 3866.9          | -0.5 [Ne iii] 68.74 |
| 3881.4a         | 2.4 He i 88.65 | PC |
| 3886.4          | -10.9 He i 88.65 | ct H8 3889 |
| 3961.7a         | 0.7 PC He, He i 3964 |
| 3967.7          | -3.75 He 70.07 | bl He i 64.73 |
| 3992.5          | -1.18 N ii 95.00 |
| 4005.7          | -0.45 He i 09.27 |
| 4019.1a         | 1.1 He i 26.19 | PC |
| 4024.3          | -2.3 He i 26.19 |
| 4086.4          | -1.7 Si iv 88.86 |
| 4090.8a         | -1.0 PC Hδ, N iii 4097 |
| 4095.0          | -2.6: N iii 97.31 | bl 4101 |
| 4099.8          | -8.5 Hδ 01.74 | bl N iii 03.37 |
| 4112.3          | -2.1 Si iv 16.10 |
Fig. 4.— Spectral variation of GR 290 during 2003–2010. Ordinates are fluxes normalized to the continuum, with vertical offsets. As for comparison, we show on the top the Cima Ekar December 2004 spectrum of the Of/WN9 star UIT 3 in M 33 (see Viotti et al. 2006). The WIYN and WHT spectra of September 2006 and December 2008 have been degraded to the resolution of the Loiano spectra. The Cima Ekar 2004 spectra of GR 290 and UIT 3 have a slightly lower spectral resolution than those taken with the Loiano telescope, so that the 4630–4660 Å, He II 4686 Å and He I 4713 Å emissions are less resolved. The vertical bars at the bottom mark the following emission lines: He I 4471 Å, the 4630–4670 Å blend, He II 4686 Å, He I 4713 Å, Hβ, He I 4922 Å, [O III]+N II 5007 Å, He I 5016 Å, and He I 5048 Å.

Fig. 5.— Log equivalent widths of He I 5876 Å versus He II 4686 Å for GR 290 during 2003–2010. The arrows mark the 2004 observations when the He II line was not measurable. The dotted lines mark the approximate boundaries of different spectral classes according to Crowther & Smith (1997) for galactic and LMC stars. The error bar of the measurements is shown on the lower right. The filled circle indicates the position of the Of/WN9 star UIT3 in M 33.
Fig. 6.— The historical light curve of GR 290 in the \( B \)-band, based on the photographic 1962–1978 survey of Romano (1978, diamonds), on the photographic 1982–1990 monitoring and \( B \)-survey (June 1999) of Kurtev et al. (2001, filled squares), and on our 2003–2010 \( B \)-monitoring (filled triangles). The hatched area contains the photographic Sternberg Astronomical Institute and Baldone observations obtained from 1972 to 2000, and reported by Sharov (1990), Sholukova et al. (2002), and Maryeva & Abolmasov (2010). The original photographic observations have been converted into Johnson’s \( B \) magnitudes using the relation: \( B = 1.064 \, \text{m}_{\text{ph}} - 0.831 \) (see Kurtev et al. 2001, and Sholukhova et al. 2002). The proposed times of the light minima and maxima are indicated by arrows.

Fig. 7.— GR 290: the spectrum–luminosity anticorrelation during 2003–2010. The equivalent widths of He \( \text{II} \) 4686 Å (stars), He \( \text{I} \) 5876 Å (open triangles), and of the 4630–4700 Å blend (stars), are plotted against the visual magnitude of GR 290.
| λ | W<sub>eq</sub> | ident. | remarks |
|---|---|---|---|
| 4119.1 | -1.2 | He i 20.82 | bl 4116 |
| 4140.8 | -1.2 | He i 43.76 | |
| 4324.0 | -0.6 | N iii 27.69 ? | bw Hγ ? |
| 4337.5 | -6.8 | Hγ 40.47 | |
| 4375.6 | -0.8 | | bw 4387 ? |
| 4385.4 | -2.2 | He i 87.93 | |
| 4444.8 | -0.7 | | n.i. |
| 4463.5a | 2.1 | He i 71.48 | PC |
| 4469.0 | -5.5 | He i 71.48 | |
| 4481.8 | -0.2 | Si iv 85.66 | W&R |
| 4501.0 | -0.5 | Si iv 04.09 | W&R |
| 4511.3 | -0.6 | N iii 14.85 | |
| 4536.3a | 0.5 | He II 41.59 | |
| 4546.4 | -2.2 | Si iii 52.65 | |
| 4565.5 | -1.1 | Si iii 67.87 | |
| 4630.5 | -4.0 | N iii 34.14 | |
| 4637.3 | -6.2 | N iii 40.64 | bl N iii 41.90 |
| 4645.6 | -4.0 | C iii 47.40 | bl C iii 50.16, 51.35 |
| 4654.4 | -3.8 | [Fe iii] 58.05 | |
| 4682.0 | -17 | He II 85.68 | narrow+broad |
| 4697.9 | -1.7 | [Fe iii] 01.53 | |
| 4705.1a | 1.3 | He i 13.15 | PC |
| 4709.5 | -3.0 | He i 13.15 | |
| 4858.2 | -18 | Hβ 61.33 | |
| 4918.7 | -2.2 | He i 21.93 | |
| 4954.6 | -0.7 | [O iii] 58.91 | |
| 5002.9 | -3.4 | [O iii] 06.84 | ct N ii m.19,24 |
| 5012.5 | -4.5 | He i 15.68 | |
| 5044.3 | -1.4 | He i 47.74 | |
| 5264.9 | -2.8 | [Fe iii] 70.42 | |
| 5672.2 | -1.5 | N ii 79.56 | bl N ii 76.02 |
| 5690.0 | -1.6 | C iii 95.92 | |
| 5748.3 | -3.1 | [N ii] 54.8 | |
| 5865.7a | 1.9 | He i 75.62 | PC |
| 5871.9 | -29 | He i 75.62 | |
| 6307.2 | -1.6 | [S iii] 12.06 | He i 10.83 ? |
| 6476.3 | -1.0 | N ii 82.07 | |
| 6540.5 | -2.9 | [N ii] 48.1 | |
| 6557.9 | -121 | Hα 62.82 | |
| 6578.1 | -8.5 | [N ii] 83.6 | |
| 6604.5 | -2.4 | N ii 10.58 | bl ? |
Table 2—Continued

| $\lambda^a$ | $W_{eq}^b$ | ident. | remarks$^c$ |
|------------|------------|--------|-------------|
| 6671.8     | -25        | He i 78.12 |
| 6693.6     | -1.2       | n.i.   | n.i. bl 6678 |
| 7050.0a    | 1.3        | He i 65.19 | PC |
| 7059.8     | -25        | He i 65.19 |
| 7129.3     | -2.4       | [A iii] 35.8 |
| 7275       | -7         | He i 81.35 |
| 7319       | -2.5       | [O ii] 19.91 ? |
| 7742       | -0.6       | [A iii] 51.5? |
| 7882       | -3         | n.i., double |
| 8660       | P13        | 65.02 |
| 8747       | P12        | 50.48 |
| 8858       | P11        | 62.79 |
| 9010       | P10        | 14.91 |
| 9060       | [S iii]    | 69.4 | strong |
| 9222       | P9         | 29.02 | strong |
| 9528       | [S iii]    | 32.1 | strong |
| 9542       | P8         | 45.97 | bl 9532 |
| 9698       | He i       | 02.66 |
| 10022      | Pδ         | 49.38 |

$^a$Observed wavelengths. $a$: absorption line.

$^b$Equivalent widths in Å, negative for emission lines.

$^c$Remarks: n.i.: not identified. bw: possibly blue wing of the nearby line cut by its P Cygni absorption component. PC: P Cygni absorption component. ct: contributing line. bl: blended with nearby line. m: multiplet number. W&R: lines identified by Werner & Rauch (2001).
Table 3: The variable spectrum of GR 290

| date/target | V  | sp. type | sp. type | Ha | λ4630-4700 | 4686 | 5876 | remarks |
|-------------|----|----------|----------|----|------------|------|------|---------|
| 2003 Feb. 02 | 17.70 | WN9      |          | 105| 18         | 7    | 20   | Loiano  |
| 2004 Feb. 14 | 17.56 | WN11     |          | 100| 8          | n.m. | 23   | Cima Elar|
| 2004 Dec. 07 | 17.18 | WN11     |          | 118| 7          | n.m. | 24   | Cima Elar|
| 2005 Jan. 13  | 17.36 | WN11     |          | 122| 14         | 0.2  | 21   | Loiano  |
| 2006 Dec. 14  | 18.50 | WN9      | WN9      | 135| 44         | 12   | 33   | Loiano  |
| 2007 Jan. 29  | 18.57 | WN8-9    |          | 126| 44         | 17   | 27   | Loiano  |
| 2008 Feb. 07  | 18.62 | WN8      |          | 129| 47         | 25   | 23   | Loiano  |
| 2008 Sep. 08  | (18.6)| WN9      |          | 120| 36         | 11   | 27   | Loiano  |
| 2008 Dec. 04  | 18.6  | WN8-9    | WN9      | 130| 40         | 18   | 27   | WHT     |
| 2010 Jan. 21  | 18.38 | WN9      |          | 120| 38         | 14   | 23   | Loiano  |

\(^a\)New and revised old equivalent widths of the emission lines in Å.

\(^b\)Equivalent spectral types for GR 290 according to the diagram of Crowther & Smith (1997).

\(^c\)Spectral types from the mid resolution WIYN and WHT spectra.

\(^d\)Including the line wings and the [N ii] lines.

\(^e\)The blend includes [Fe iii] 4701 Å. He i 4713 Å is excluded.