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OPTICAL SPECTROPHOTOMETRIC MONITORING OF THE EXTREME LUMINOUS BLUE VARIABLE STAR GR 290 (ROMANO'S STAR) IN M 33*

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ABSTRACT

We study the long-term, S Dor-type variability and the present hot phase of the luminous blue variable (LBV) star GR 290 (Romano's Star) in M 33 in order to investigate possible links between the LBV and the late, nitrogen sequence Wolf–Rayet Stars (WNL) stages of very massive stars. We use intermediate-resolution spectra, obtained with the William Herschel Telescope (WHT) in 2008 December, when GR 290 was at minimum ($V = \sim 18.6$), as well as new low-resolution spectra and *BVRI* photometry obtained with the Loiano and Cima Ekar telescopes during 2007–2010. We identify more than 80 emission lines in the 3100–10000 Å range covered by the WHT spectra, belonging to different species: the hydrogen Balmer and Paschen series, neutral and ionized helium, C III, N II–III, S IV, Si III–IV, and many forbidden lines of [N II], [O III], [S III], [A III], [Ne III], and [Fe III]. Many lines, especially the He I triplets, show a P Cygni profile with an *a*–*e* radial velocity difference of -300 to -500 km s^{-1}. The shape of the 4630–4713 Å emission blend and of other emission lines resembles that of WN9 stars; the blend deconvolution shows that the He II 4686 Å has a strong broad component with FWHM $\simeq$ 1700 km s^{-1}. During 2003–2010 the star underwent large spectral variations, best seen in the 4630–4686 Å emission feature. Using the late-WN spectral types of Crowther & Smith, GR 290 apparently varied between the WN11 and WN8–9 spectral types; the hotter the star was the fainter its visual magnitude was. This spectrum–visual luminosity anticorrelation of GR 290 is reminiscent of the behavior of the best-studied LBVs, such as S Dor and AG Car. During the 2008 minimum, we found a significant decrease in bolometric luminosity, which could be attributed to absorption by newly formed circumstellar matter. We suggest that the broad 4686 Å line and the optical continuum formed in a central Wolf–Rayet region, while the narrow emission line spectrum originated in an extended, slowly expanding envelope which 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 a phase preceding the transition from the LBV state to a late-WN type.

Key words: galaxies: individual (M 33) – stars: evolution – stars: individual (GR 290) – stars: variables: general – stars: Wolf–Rayet

Online-only material: color figures

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 (LMC), recognized that the distribution of the most luminous hot stars in the Hertzsprung–Russell (H-R) diagram defines a locus 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 $\log(L/L_{\odot}) \simeq 5.8$, these authors suggested that the most massive stars ($M \geqslant 60\ M_{\odot}$) do not evolve to cooler temperatures as stars of intermediate and low mass do. Episodes characterized by a high mass-loss rate, such as those observed in η Car, P Cyg, S Dor, and the Hubble–Sandage variables in M 31 and M 33, are responsible for this failure to evolve to cooler states. 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 as normal those cycles in which changes of up to 1–2 mag 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 for the prototype of this class in the LMC (van Genderen 1979, 2001). In a few cases, changes of 3 mag or more in the visual band have been recorded, such as the so-called giant eruptions observed for η Car in the 19th century and P Cyg in the 17th century (Humphreys & Davidson 1994).

Since 2003, we have been extensively monitored LBVs in M 33 (Viotti et al. 2006), mostly through 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, Romano's Star (GR 290) is the most interesting both for its high temperature and luminosity and for its large optical variations (Romano 1978; Kurtev et al. 2001; Sholukhova et al. 2002; Polcaro et al. 2003; Viotti et al. 2006; Maryeva & Abolmasov 2010). GR 290 is an LBV placed at about 4.2 kpc to the northeast of the center of M 33, near the young OB association OB 89. Its historical light

* Based on observations collected with the 4.2 m William Herschel Telescope of the Isaac Newton Group of Telescopes, Roque de los Muchachos, La Palma, Spain, the 1.52 m Cassini Telescope at Loiano of the Bologna Astronomical Observatory, and the 1.82 m Copernico Telescope at Cima Ekar, Asiago, of the Padova Astronomical Observatory.

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 7	18.52(0.07)	18.62(0.04)	18.41(0.09)		Loiano
2008 Sep 8			18.2(0.1)		Loiano
2008 Dec 6	18.2(0.2)	18.6(0.2)	18.2(0.2)		Cima Ekar
2009 Feb 9	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

curve is characterized by ample long-term variations between 16.2 and 18.2 in the *B* band (e.g., Romano 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 Section 2, we summarize the new observations and the procedures of data analysis. In Section 3, we describe the intermediate-resolution spectrum obtained with the William Herschel Telescope (WHT) in 2008 December, and analyze the spectral variations observed during 2003–2010. In Section 4 we discuss our results and offer some final considerations in Section 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 2003 February and 2006 December have been discussed in our previous papers (Polcaro et al. 2003; Viotti et al. 2006, 2007). New low-resolution spectra were obtained in 2007 January, 2008 January–February, 2008 September, 2009 February, and 2010 January with the Loiano telescope. All of these spectra, taken with the broad wavelength range grism-4 instrumental setup, have a dispersion of ∼4 Å pixel^{-1}. In addition, new *BVRI* 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 *BVRI* magnitudes are derived as described in our previous papers. In Figure 1, we plot all of our *BVR* measurements during 2003–2010.

Intermediate-resolution spectra of GR 290 were obtained on 2008 December 4 with the ISIS spectrograph mounted at the 4.2 m 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^{-1} and 1.81 Å pixel^{-1}. Two exposures for each wavelength range were obtained with a signal-to-noise ratio for the continuum of about 30 and 40 near 4200 Å and 6500 Å for the blue and red spectra, respectively. All spectra were analyzed using standard IRAF procedures.[5] Multi-Gaussian fits were used to analyze line blends and P Cygni profiles. We also made use of a blue spectrum of GR 290 obtained in 2006 September at the WIYN 3.5 m telescope with a dispersion of 0.53 Å pixel^{-1} (see Massey et al. 2007), kindly provided by Philip Massey.

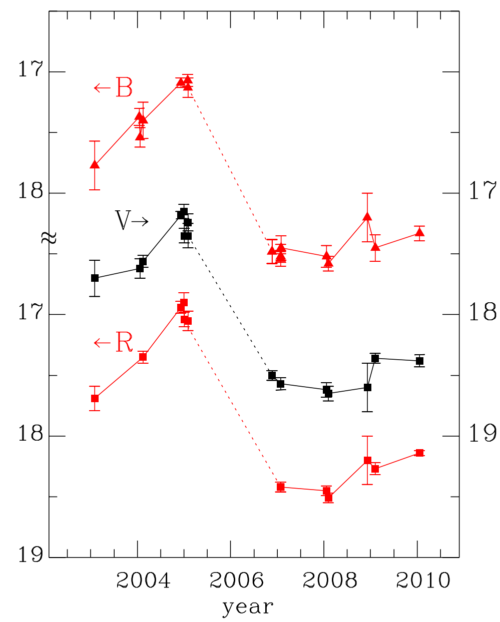

Figure 1. Recent light curve of GR 290 from 2003 February to 2010 January in the *B*, *V*, and *R* bands. For clarity, the different curves have been vertically shifted. As indicated by arrows next to *BVR* labels in the plot, *B* magnitudes are in the upper part of the left scale and*R* magnitudes are in the lower part, while the right scale refers to the *V* magnitudes.

(A color version of this figure is available in the online journal.)

3. THE SPECTRUM OF GR 290

3.1. The 2008 December Spectrum

The 2008 December spectrum of GR 290 is shown in Figures 2(a)–(i). For the line identifications, we have made use of the rich literature on the spectra of emission-line stars, including, symbiotic, *B*-emission, and late, nitrogen sequence Wolf–Rayet (WNL) stars, and the NIST database.[6] The list of line identifications is given in Table 2. The observed wavelength and W_{eq} values listed in the table are averages (when available) of 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 Figure 2, all of the triplet and several of the singlet transition He I 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 which originated from the metastable level 2^3S (Figures 2(a) and (b)).

Near the strong 5015 Å He I line, about 11 Å to the blue side, an intense emission line is visible (Figure 2(f)). The profile

[5] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[6] Ralchenko et al. (2008). NIST Atomic Spectra Database (version 3.1.5). Available online at http://physics.nist.gov/asd3 (2009 September 3).

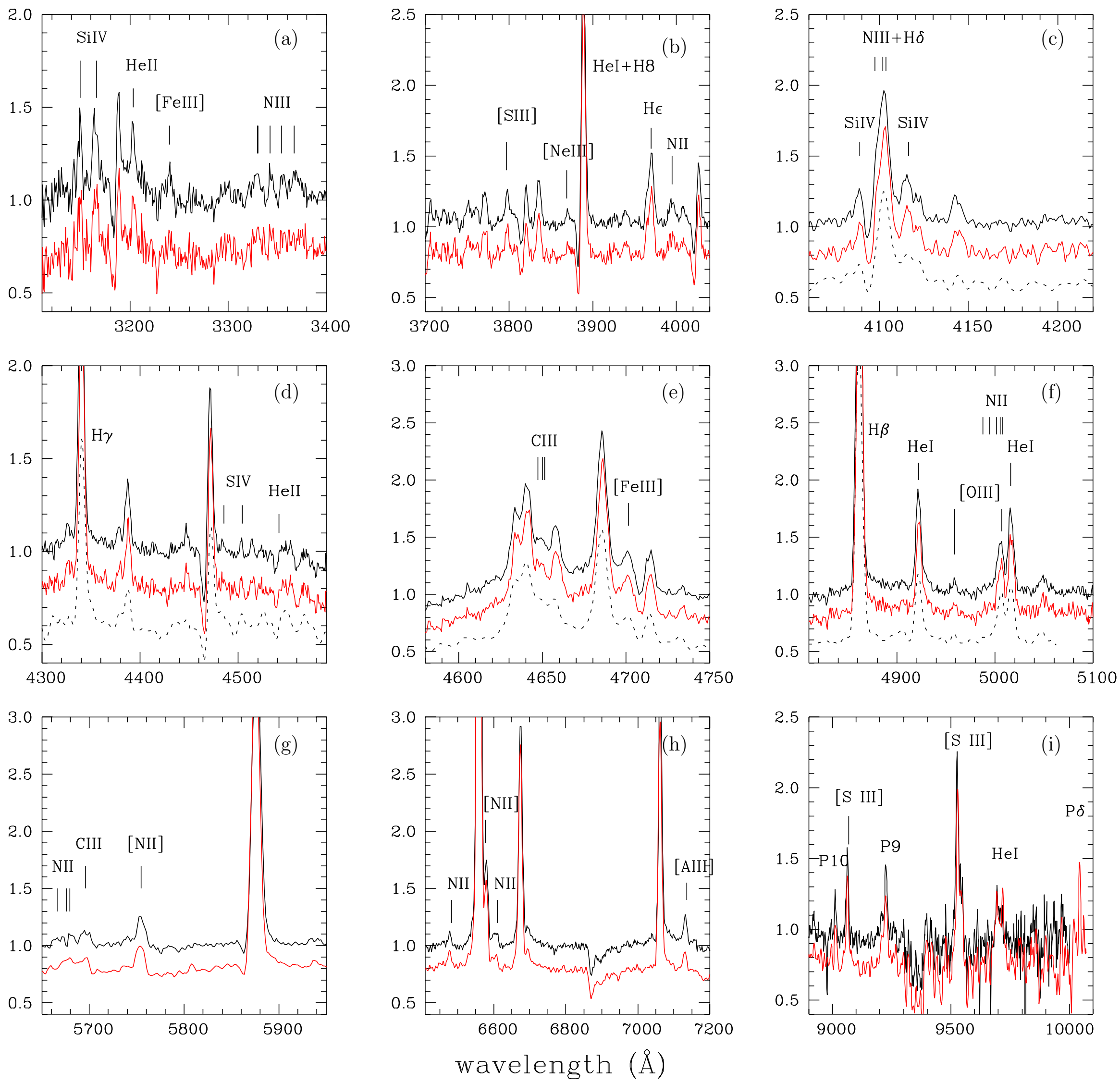

Figure 2. 2008 spectrum of GR 290 with some line identification. Two exposures are shown for each spectral region, with a vertical offset of −0.2 for the less exposed one (in red), to aid with assessing the presence of the various spectral features. In panels (c)–(f), the WIYN spectrum of 2006 September 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.

(A color version of this figure is available in the online journal.)

of the blend is similar to that observed in 2006 September 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 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 $3d^3P^0$ and $3d^3F^0$ 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 [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 [O III] doublet, seems rather to favor the identification of the 5003 Å emission with [O III]. The observed 5007/4959 intensity ratio of 4.3 ± 2.0 is not in disagreement with the theoretical ratio of the [O III] doublet, although we think that both the N II blend and the [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 [O II]. The presence of the [O III] doublet emission lines during minimum has been recently confirmed by the higher resolution observations described by Maryeva & Abolmasov (2010). The [O III] doublet has also been strongly seen 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, which is part of the broad 4600–4700 Å blend, the so-called *f*-feature, will be discussed in more detail in Section 3.2. Also the Paschen-β He II 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

Table 2
The 2008 December WHT Spectrum of GR 290

λ[a]	W_{eq}[b]	Ident.	Remarks[c]
3147	−1.9 :	Si IV 49.56	
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
3582.2a	0.49	He I 87.25	PC
3585.3	−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 Hϵ, He I 3964
3967.7	−3.75	Hϵ 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	
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	S IV 85.66	W&R
4501.0	−0.5	S 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 NIII 41.90
4645.6:	−4 :	C III 47.40	bl CIII 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 ?
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	

Notes.
[a] Observed wavelengths. a: absorption line.
[b] Equivalent widths in Å, negative for emission lines.
[c] 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).

of 2006 September (Figure 2(d)). This line can be identified with the Brackett-ϵ He II 4541 Å line, slightly blueshifted 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 III blend, that falls below the continuum level (Figure 2(c)), has to be attributed to a P Cygni absorption component of Hδ, with a possible contribution of the N III 4097 Å line. The steeper blue side of Hβ and Hγ also suggests the presence of an unresolved weak P Cygni component (Figures 2(d) and (f)). The near-infrared region is noisy and does not allow to resolve the profile of the Paschen lines (e.g., Figure 2(i)).

In addition to N III, singly ionized nitrogen is also present with several lines, most of which are thought to be selectively excited (see Walborn 2001). C III is present with a weak emission line at 5695 Å and with the blue triplet at 4647–50–51 Å with a weak peak in between the N III 4641 Å and the [Fe III] 4658 Å emission lines (see also Section 3.2). Si 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 Å (Figure 2(d)) have been identified with the S IV recombination lines 4485.662 Å and 4504.093 Å belonging to the high excitation $2s^2 4d^2 D$–$3s^2 4f^2 F^o$ 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 III] discussed above, the spectrum of GR 290 displays forbidden lines of doubly ionized sulfur (e.g., 3797 Å, 6312 Å, 9532 Å), argon (7136 Å, 7751 Å), neon (3869 Å), and iron (3240 Å, 5270 Å), as well as the yellow and red lines of [N 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 N–S 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 II] and [Fe II] in GR 290 is in agreement with its present ionization level which is higher than that in other LBVs.

3.2. The 4650 Å Emission Blend

Of particular interest is the strong 4640–4700 Å emission feature that is a blend of emission lines belonging to many different species including N II, N III, C III, [Fe III], and He II (Figure 3). We have tentatively fitted the 4620–4713 Å spectral region with a combination of the following lines: N II 4621.39–30.54, N III 4634.14–40.64–41.85, C III 4647.42–50.25–51.47, [Fe III] 4658.05–67.01, He II 4685.68, [Fe III] 4701.53, and He I 4713.15. For all of the lines we have assumed the same FWHM of 6.2 Å, uncorrected for spectral resolution. A P Cygni profile has been used for the He I 4713 Å line assuming a radial velocity difference of −220 km s^{-1}for the absorption and emission components. However, the fit does not fully account for the flux level around 4670 and 4690 Å. We attribute this excess to the presence of the broad wings of the He II 4686 Å line. This is better seen in the lower panel of Figure 3, where we show the spectral region after subtraction of the contribution of all the above emission lines except He II 4686 Å. The residual is fitted by two Gaussians with FWHM = 6.2 Å and 26.5 Å for the narrow and broad components, respectively. The width of the latter component corresponds to a Doppler broadening of ∼1000 km s^{-1}. The derived broad/narrow flux ratio is equal to 1.4. We cannot exclude a minor contribution of other weaker lines, such as the C IV 4658 Å line, to the 4650 Å blend although the absence of a strong C IV doublet at 5801–12 Å would argue against its presence in the 4650 Å blend. The final fit is shown in the upper panel of Figure 3. In the fit, the blue tail of the 4650 Å blend is attributed to N II, but it could be more likely attributed to a broad component of the N III 4634–42 Å triplet. If this is the case, we estimate that its strength should be 30%–50% of the 4686 Å 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 us to perform the same analysis as for the He II 4686 Å line.

Such a double profile, with narrow and broader emission components, has been observed in the Ofpe/WN9–WN10h star R99 in the LMC (Crowther & Smith 1997). In that case the broad component is redshifted with an FWHM of 600 km s^{-1}. We also recall that *Hubble Space Telescope*/Space Telescope Imaging Spectrograph observations of η Car allowed Hillier et al. (2001) to resolve and study the spectrum of the central source (0.1 arcsec) and to show that it has mainly broad (FWHM ≈ 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. It is therefore likely that a similar scenario might account for the double components 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 circumstellar, slowly expanding nebula ionized by the UV radiation of the central source.

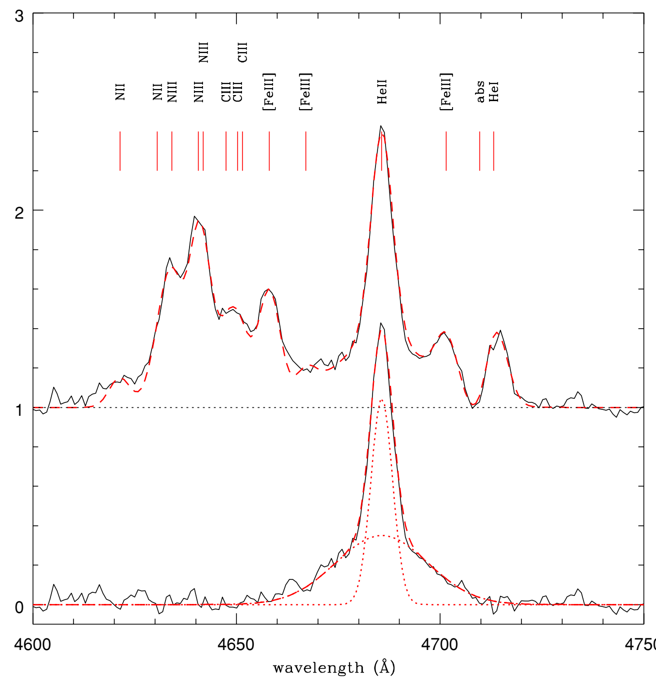

Figure 3. Upper panel: the 4620–4713 Å spectral range, as observed in 2008 December, fitted (dashed line) by a combination of selected emission lines (marked by vertical bars and identified in the picture). The wavelength scale of the spectrum has been shifted to fit the laboratory wavelength. Both broad and narrow components have been included for the He II 4686 Å line (see the lower panel). For the He I 4713 line, a violetshifted 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).

(A color version of this figure is available in the online journal.)

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 some variability during the years, with the 4630–4700 Å emission blend varying the most. To illustrate this, in Figure 4 we have plotted 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 this figure, the spectra of GR 290 taken at WIYN in 2006 September and at WHT in 2008 December have been degraded to the Loiano spectral resolution. The Cima Ekar spectra of GR 290 from 2004 February and December, and of UIT 3 have a slightly lower spectral resolution than those taken with the Loiano telescope, so that the 4630–4660 Å feature and the He II 4686 Å and He I 4713 Å lines are poorly

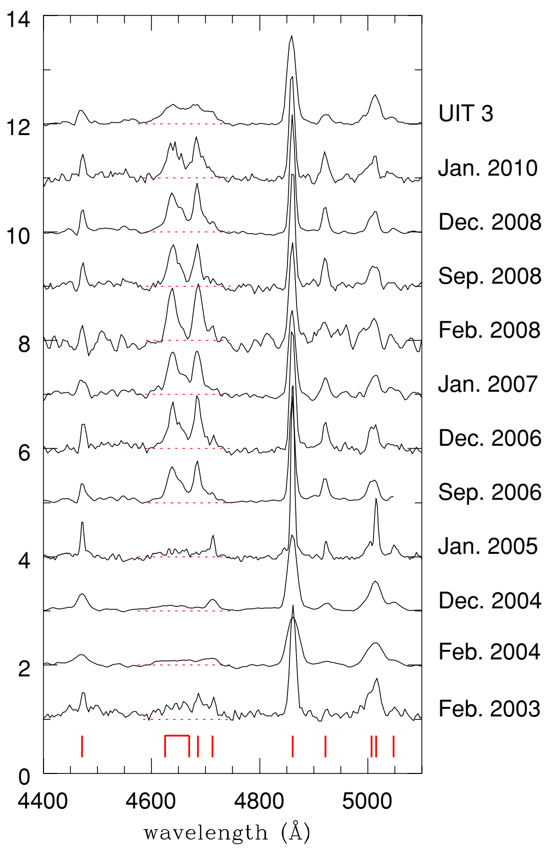

Figure 4. Spectral variation of GR 290 during 2003–2010. Ordinates are fluxes normalized to the continuum, with vertical offsets. For comparison, we show on the top the Cima Ekar 2004 December spectrum of the Of/WN9 star UIT 3 in M 33 (see Viotti et al. 2006). The WIYN and WHT spectra of 2006 September and 2008 December 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.

(A color version of this figure is available in the online journal.)

resolved. The Loiano 2005 January spectrum was obtained with the higher resolution grism 7. From this comparison we can see that, in coinciding with the 2006 minimum, the 4630–4700 Å blend became prominent and has stayed so since, with maximum strength in the 2008 January–February 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 in Section 3.2. From Table 3, one can see that after 2003 February the equivalent width of He II 4686 Å has dramatically decreased until reaching a minimum value in 2004–2005. In this epoch, this line was absent, or too weak to be distinguished within the blend in our low-resolution 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 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 a 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 which was followed by a slight decrease in the following years.

During mid-2006 up to 2010 January, GR 290 exhibited a spectrum very similar to that of late-WN stars. Therefore, in order to assign 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 and 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 have been classified as a 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) versus W_{eq}(4686) diagram used for classifying WNL stars (Crowther & Smith 1997). In the diagram shown in Figure 5, the areas identifying the WN and Of spectral types are marked and labeled. According to this classification scheme,

Table 3
The Variable Spectrum of GR 290[a]

Date/Target	V	Sp. Type[b]	Sp. Type[c]	Hα[d]	4630–4700[e]	4686	5876	Remarks
2003 Feb 2	17.70	WN9		105	18	7	20	Loiano
2004 Feb 14	17.56	WN11		100	8	n.m.	23	Cima Ekar
2004 Dec 7	17.18	WN11		118	7	n.m.	24	Cima Ekar
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 7	18.62	WN8		129	47	25	23	Loiano
2008 Sep 8	(18.6)	WN9		120	36	11	27	Loiano
2008 Dec 4	18.6	WN8–9	WN9	130	40	18	27	WHT
2010 Jan 21	18.38	WN9		120	38	14	23	Loiano

Notes.
[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] Includes the line wings and the [N II] lines.
[e] The blend includes [Fe III] 4701 Å. He I 4713 Å is excluded.

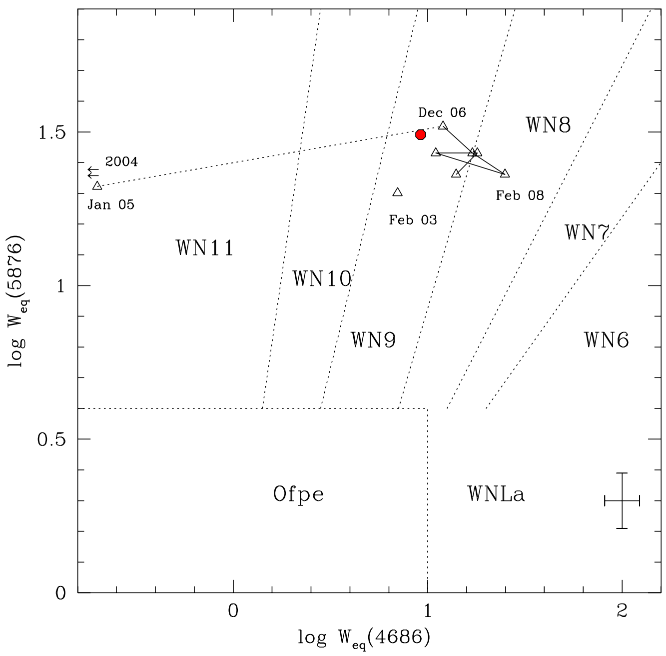

Figure 5. log equivalent widths of He I 5876 Å vs. He II 4686 Å for GR 290 during 2003–2010. The arrows mark the 2004 observations when the He II line was not measurable. The dotted lines mark the approximate boundaries of different spectral classes according to Crowther & Smith (1997) for galactic and LMC stars. The error bar of the measurements is shown in the lower right. The filled circle indicates the position of the Of/WN9 star UIT 3 in M 33.

(A color version of this figure is available in the online journal.)

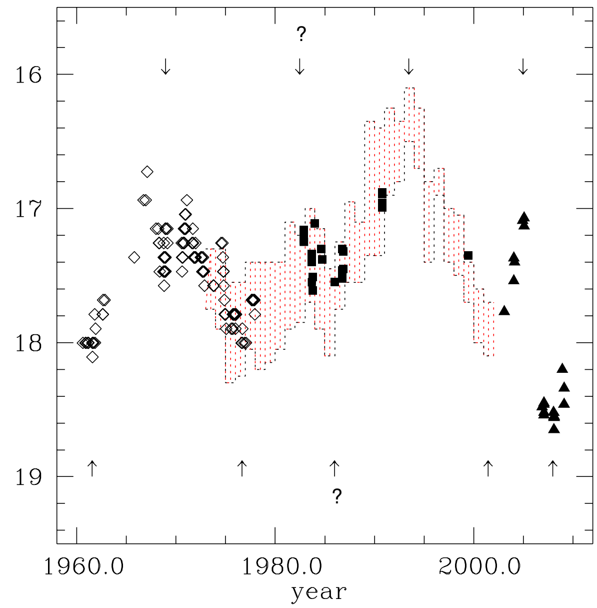

Figure 6. Historical light curve of GR 290 in the B band, based on the 1962–1978 photographic survey of Romano (1978, diamonds), on the 1982–1990 photographic monitoring and B survey (1999 June) of Kurtev et al. (2001, filled squares), and on our 2003–2010 B monitoring (filled triangles). The hatched area contains the photographic Sternberg Astronomical Institute and Baldone observations obtained from 1972 to 2000, and reported by Sharov (1990), Sholukhova et al. (2002), and Maryeva & Abolmasov (2010). The original photographic observations have been converted into Johnson's B magnitudes using the relation: $B = 1.064m_{\rm ph} - 0.831$ (see Kurtev et al. 2001; Sholukhova et al. 2002). The proposed times of light minima and maxima are indicated by arrows.

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GR 290 changed spectral subtype from WN9 in 2003 to WN11 in 2004–2005 then returned to WN9 again in 2006 where it has remained since. At the beginning of 2008 the star reached its hottest state with the He II 4686 Å line being as strong as in the LMC and galactic WN8 stars (Figure 5). However, in our low-resolution spectra of 2008 January–February, there is no evidence for the presence of a prominent N IV 4067 Å emission line in particular which should be present, according, e.g., to Crowther & Smith (1997), in a spectrum of WN8 subtype, nor has this line been identified in the high-resolution spectrum of 2008 January discussed by Maryeva & Abolmasov (2010).

Both the WIYN 2006 September and the WHT 2008 December 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, which is 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 Figure 6. Since 1960, GR 290 has 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 1967–1975 and probably in 1980–1985, both with B around 17.2, and the strongest one was recorded in 1993–1994 with $B_{\rm max} = 16.2$. The recent light curve is illustrated in Figure 1. Between 2003 February and 2004 December–2005 February, 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 1 mag fainter than in the 1993 maximum, but comparable to the two previous maxima. In 2006 November, 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 μm and 4.5 μm bands between 2004 January and 2005 January, followed in 2005 August 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 started in 2005. Since, according to Massey et al. (2007) and Maryeva & Abolmasov (2010), in 2006 August–September 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 $\geqslant +0.10$ 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 Figure 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

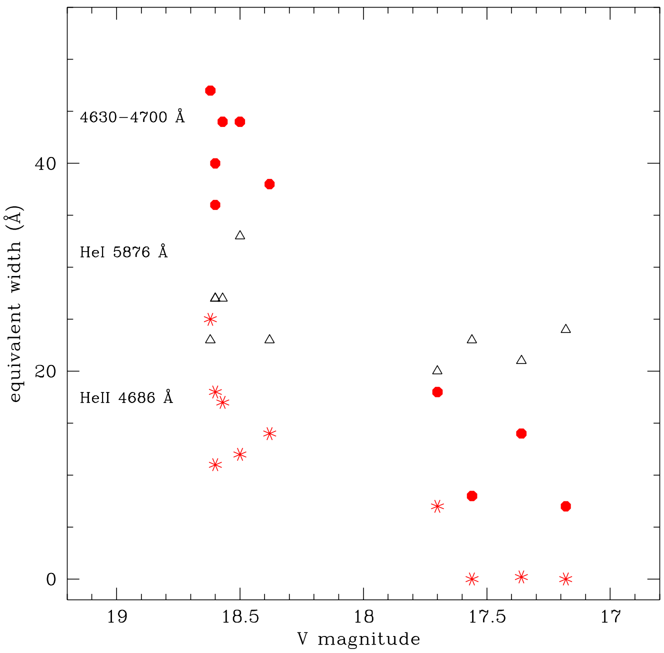

Figure 7. GR 290: the spectrum–luminosity anticorrelation during 2003–2010. The equivalent widths of He II 4686 Å (stars), He I 5876 Å (open triangles), and the 4630–4700 Å blend (stars) are plotted against the visual magnitude of GR 290.

(A color version of this figure is available in the online journal.)

illustrated in Figure 7 where the equivalent width of these high-temperature features is plotted against the visual magnitude. The hot phase corresponds to the W_{eq} value of ∼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 ≈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_{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 1998 September and 1999 July at the 6 m BTA telescope during the descending luminosity phase, are described by Fabrika et al. (2005). This 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 1992 October 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 the top of Figure 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 when LBVs 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 bluing of the color index. The spectrum–visual luminosity anticorrelation observed in GR 290 is reminiscent of the behavior of the best-studied LBVs, such as S Dor and R127 in the 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 behavior of one stellar component of the massive close binary system HD 5980. This star seems to have displayed an early-type Wolf–Rayet spectrum of the nitrogen sequence during the long-lasting phase prior to the 1993–1994 outbursts when its spectrum became WN11–B1.5 (Koenigsberger 2004; Koenigsberger et al. 2010). No significant bluing 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 could be inaccurate for such a faint object.

4.2. How Luminous is GR 290?

In order to put GR 290 in the context of other known LBVs, it is necessary to estimate the star's luminosity in its various phases. The blackbody fit of the optical–near-infrared energy distribution of GR 290 in 2004 December, when the star had $V = 17.2$ and a WN11-type spectrum, provides a blackbody 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). From the analysis of late-WN stars in the LMC, Crowther & Smith (1997), derived an effective temperature of 25,000–27,000 K and a bolometric correction around −2.8 for spectral type WN11. Groh et al. (2009) derived $T_{\mathrm{eff}} = 22{,}800$ 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 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 for the 2004 December spectrum of GR 290, we derive $M_{\mathrm{bol}} = -10.6$, or $L_{\mathrm{bol}} = 1.4 \times 10^6\ L_\odot$, with an assumed distance modulus for M 33 of 24.8 (from Kim et al. 2002). Then, if we assume $T_{\mathrm{eff}} = 22{,}800$ K for GR 290, we derive an effective radius $R_{\mathrm{eff}} \simeq 76\ R_\odot$.

At the 2008 February deep minimum the star was about 1.5 mag fainter in V than in 2004 December, while its spectrum was intermediate between WN9 and WN8. Assuming a bolometric correction of −3.0/−3.3 (e.g., Nugis & Lamers 2000) for this phase, and the same E_{B-V} as above, we obtain $M_{\mathrm{bol}} \simeq -9.8$, or $L_{\mathrm{bol}} \simeq 0.66 \times 10^6 L_\odot$, i.e., a bolometric luminosity which is about half that of 2004 December. Using an effective temperature suitable for WN9 stars, ∼28,000 K, we obtain an effective radius of ∼35 $R_\odot$.

At the highest maximum of 1993, GR 290 was 0.9 mag brighter in B than in 2004 December. 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 to that of 2004 December. 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 2004 December.

If we follow what is generally known for LBV behavior, the counter-trend of the visual luminosity and the emission-line excitation in GR 290 would suggest a variation with more-or-less constant bolometric luminosity, similar 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 2004 December. Of course, our luminosity estimates critically depend on the assumed values of the bolometric corrections. According to the proposed model atmospheres also discussed above, the range of the uncertainty on the BC difference between the two epochs is likely to be around ± 0.3 mag. However, even taking this uncertainty into account, the luminosity difference of about a factor of 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 2008 February spectrum. We suggest that this bolometric luminosity decrease could be only apparent, and due to a $\sim$0.8 mag extinction of the visual light, in addition to the interstellar one. In this hypothesis, the light from GR 290 in 2008 February 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 in the mid-infrared flux.

We finally remark that, although a change in L_{bol} during S Dor variations for LBV stars is difficult to interpret in light of the current models, 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), such a 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 et al. (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 has been no independent evidence, such as a very high mass-loss rate, that such a mechanism has been at work since 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 He I emission lines with a P Cygni profile, broad and narrow components are present in the He II 4686 Å line with comparable strength. The broad component has been identified in the mid-resolution spectrum of GR 290 obtained in 2008 December, during the low luminosity phase of the star. Similar broad wings are not seen in the prominent hydrogen lines. The He II broad component indicates the presence of a high-velocity ($\sim$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 He II 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). 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 He II 4686 Å which 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 large spectrophotometric variability. In the evolutionary sequence of very massive stars, the position of stars with a spectrum similar to the position of luminous late-WN-type stars with hydrogen in their spectra, designated as WNH stars by Smith & Conti (2008), is still under debate. They may be in an early evolutionary phase of core He burning with a H envelope which has 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 a consequence of their high luminosity with mass-loss rates determined by the Eddington luminosity limit being exceeded. GR 290 has a luminosity of around 10^6 $L_{\odot}$, which is of the same order expected for very luminous WNH stars, except that GR 290 displays large long-term photometric variations typical of LBVs, while WNH stars do not. An evolutionary development has been suggested in the literature in which very massive stars with initial mass larger than $\sim$40 $M_{\odot}$ display LBV activity very early in their evolution, perhaps even while in a core H burning stage. 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 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 behavior observed in recent years, we cannot exclude the possibility that the star is going through a transition phase, perhaps developing the expected WN8 spectrum after some time.

5. CONCLUSIONS

We have used recent spectrophotometric data together with existing data from the literature to study the long-term behavior of the LBV star GR 290. This star is peculiar because of its high excitation temperature at minimum, which is 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 to be the case for LBVs. There are few other LBV objects that exhibit such behavior. This has been explained, as discussed above, by conversion of radiative power into mechanical power. We advance the alternative hypothesis that the luminosity decrease may only be apparent and may 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 probably not too far from the end of this phase, and may be evolving toward a late-WN-type star. This is of course only a hypothesis that awaits further tests on surface chemical abundances in order to determine the star's actual evolutionary stage.

Thanks are due to the Time Allocation Committee of the Isaac Newton Group of Telescopes for allocating service time at the WHT, which was fundamental for our work. We are grateful to Phil Massey for having put the 2006 September spectrum of GR 290 for analysis at our disposal, and to Alessandro Chieffi for useful discussions. We thank the anonymous referee for constructive comments and for having drawn our attention to the preprint of the article on GR 290 by Maryeva & Abolmasov. We also acknowledge the Roma Amateur Astronomy Association (ARA) and Franco Montagni for undergoing a monitoring program to alert possible luminosity variations of GR 290 and other peculiar objects on our behalf.

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