

The present status of four luminous variables in M 33^{★,★★}

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ABSTRACT

Context. Understanding the origin of the instabilities of LBVs is important for shedding light on the late evolutionary stages of massive stars and on the chemical evolution of galaxies.

Aims. To investigate the physical nature of variable stars in the upper H–R diagram, we performed a spectrophotometric study of the Romano’s star GR 290 and the Hubble–Sandage variables A, B, and C in the close galaxy M 33.

Methods. New spectroscopic and photometric data were employed in conjunction with already published data of these stars in order to derive spectral types, energy distribution and bolometric luminosities.

Results. The yellow hypergiant Var A is still at minimum, with a \sim G-type spectrum and strong H α emission ($W_{\text{eq}} \approx -35 \text{ \AA}$). Var B is in a low luminosity hot state ($V = 17.5$, $B - V = -0.15$) with very strong H α emission ($W_{\text{eq}} = -310 \text{ \AA}$). Its absolute bolometric luminosity is $0.6 \times 10^6 L_{\odot}$. Var C, at $V = 16.4$, is fainter than in the mid 1980s, but its spectrum shows the typical features of LBVs at maximum, a spectrum that is very rich in Fe II emission lines. Its L_{bol} is about $0.7 \times 10^6 L_{\odot}$. The Romano’s star GR 290 has a rich hot emission-line spectrum and is very bright with $L_{\text{bol}} = 3 \times 10^6 L_{\odot}$. During 2004 the star brightened by \sim half magnitude in each of the BVR filters.

Conclusions. Our observations confirm that Var A probably is an intermediate type hypergiant star surrounded by an expanding envelope with a collisionally excited hydrogen emission, largely obscured by dusty disk and nebula. In recent years, Var B has undergone a blueward transition in the H–R diagram, probably at constant bolometric luminosity, while Var C is in a post-maximum phase with an η Car-type spectrum. GR 290 is notable for its spectrum and luminosity, and it is likely to develop ample spectral variations in the near future, similar to those observed in AG Car.

Key words. stars: evolution – stars: variables: general – supergiants – galaxies: individual: M 33

1. Introduction

Our objects of study are four bright variable stars in M 33, three of which are found in the historical catalogue of Hubble & Sandage (1953). For their characteristics these stars are to be considered as the prototypes of the category of luminous blue variables (LBV), or S Doradus variable stars. The LBV category includes a small number of intrinsically bright ($\text{Log } L/L_{\odot} \approx 6$) hot stars, typically showing ample and irregular light variation on a very long time scale (up to several decades). Extensive reviews of their properties are to be found e.g., in Humphreys & Davidson (1994) and van Genderen (2001). Although they are rare objects, LBVs are important for understanding both the late evolutionary phases of massive stars and the chemical evolution of galaxies due to the large amounts of mass lost during this phase.

The photometric variation, along with associated spectroscopic ones, is an intriguing aspect of the LBV phenomenon. Spectroscopically, LBV stars may exhibit the spectral features

of Of/WNL stars, of B/A-type supergiants, and in a few cases, of later spectral types. In a number of well studied cases, the star is hotter when fainter in V , suggesting that the variation may take place at constant bolometric luminosity. This might not be a common feature of all LBVs, since several types of variability, which also occur on different time scales, have been identified (see e.g. van Genderen 2001). Some luminosity variations are at least partly due to extinction from a variable dust envelope, as it was the case of η Car in the mid-1800. Therefore, spectrophotometric monitoring of the widest sample of LBV in the Milky Way and in other galaxies is fundamental for unveiling the nature of the LBV phenomenon. M 33 is so far the richest among the nearby galaxies in the number of identified LBVs (see e.g. Corral 1996; Kurtev et al. 2001; Polcaro et al. 2003), probably because it is seen at a small inclination angle. Therefore it presents a good opportunity for sampling the S–Dor variability stage of a population of very massive stars. We present a spectrophotometric study here of four of the known LBVs in M 33.

2. Observations

Observations of the target stars were carried out during several observing runs between February 2003 and September 2005 at the Asiago and Loiano Observatories. This work is mostly focused on the observing run of 2004 December 6–8 during

* Based on observations collected with the 1.83 m Cima-Ekar telescope of the Padova Astronomical Observatory and with the 1.52 m Cassini telescope of the Bologna Astronomical Observatory.

** Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/458/225>

which we have obtained grating spectra of GR 290, and of the Hubble-Sandage variables A, B, and C¹ (hereafter called Var A, Var B and Var C) at the Asiago Cima Ekar 1.83 m telescope equipped with the Asiago Faint Objects Spectrometer and Camera (*AFOSC*). The grism 4 was used to cover the wavelength range 3200–7800 Å, with a resolution of 4.5 Å per pixel. A slit width projected on the sky of 2.1 arcsec ($\equiv 4.4$ pixels) was used for all the spectroscopic observations. An S/N of 40 to 80 per wavelength element was obtained for the yellow continuum for all the spectrograms, except for Var A for which the S/N was about 20. The spectra of Var B and Var C were taken simultaneously with a suitable slit rotation. For the comparison with GR 290, we obtained the grism 4 spectrum of the Ofpe/WN9 star M33-UIT003 of Massey et al. (1996) (hereafter called UIT3) and of a number of standard stars. A low-resolution spectrum of the B emission star HD 45677 (FS CMA) taken during the same observing run was utilized for the line identification of Var C (see Sect. 6). As a complement to the spectroscopic observations, we obtained multicolour 8.1×8.1 arcmin images of the four targets. The scale was 0.47 arcsec per pixel. The GR 290 field also includes the nearby associations OB 88 and OB 89.

The logbook of the December 2004 spectroscopic and photometric observations of the target stars taken at Cima Ekar is reported in Table 1. The table also reports the additional spectroscopic and photometric observations collected at Cima Ekar and with the 1.52 m Cassini telescope of the Bologna Astronomical Observatory at Loiano, equipped with *BFOSC* (Bologna Faint Objects Spectrometer and Camera). The Camera FOV was 13×13 arcmin². In addition, starting from December 2003 the field of GR 290 was monitored in *BVRI* with the 30 cm Greve telescope (see Table 3) equipped with an SITE 502 back illuminated camera. The photometric and spectroscopic data were analysed by means of standard IRAF procedures².

3. Data analysis

The Asiago spectrograms were photometrically calibrated using a number of observations of spectroscopic standard stars. In Fig. 1 we present all the individual spectrograms obtained for GR 290, Var A, Var B, and Var C in the December 2004 observing campaign. All targets except Var A were observed twice. As can be seen in Fig. 1 the differences between the absolute flux values for different spectra of the same target are of the order of 10–30%. We attribute this to the known fact that, notwithstanding all the efforts to obtain a good flux calibration, a non-quantifiable (and different from target to target) amount of light is lost through the spectrograph's aperture slit.

To check the accuracy of our absolute calibrations, we used the best exposed spectrograms of the target stars to derive the broad-band $B - V$ fluxes that are compared with the magnitudes given below. We found good agreement for GR 290 (see also Fig. 9 below) and Var C. As for Var A the fluxes corresponding to the B and V photometry are a factor 3.4 higher than those derived from the calibrated spectrogram. This is probably due either to a slightly incorrect positioning of the star in the slit or

Table 1. Log of the observations.

Date	Target	Mode	exp. (s)	obs. site
Feb. 02, 2003	GR 290	grism 4	1800	Loiano ¹
Feb. 02, 2003	GR 290	B image	300	Loiano ¹
Feb. 02, 2003	GR 290	V image	60	Loiano ¹
Feb. 02, 2003	GR 290	R image	30	Loiano ¹
Feb. 14, 2004	GR 290	grism 4	3000	Ekar
Feb. 14, 2004	GR 290	B image	600	Ekar
Feb. 14, 2004	GR 290	V images	3×120	Ekar
Feb. 14, 2004	GR 290	R images	2×240	Ekar
Dec. 06, 2004	GR 290	grism 4	3000	Ekar
Dec. 06, 2004	GR 290	grism 4	3000	Ekar
Dec. 06, 2004	GR 290	V image	180	Ekar
Dec. 06, 2004	GR 290	V image	180	Ekar
Dec. 06, 2004	GR 290	I image	180	Ekar
Dec. 07, 2004	UIT 3	grism 4	2700	Ekar
Dec. 07, 2004	GR 290	U images	2×900	Ekar
Dec. 07, 2004	GR 290	B images	3×600	Ekar
Dec. 07, 2004	Var B+C	V image	300	Ekar
Dec. 07, 2004	Var B+C	B image	300	Ekar
Dec. 07, 2004	Var B+C	grism 4	2700	Ekar
Dec. 08, 2004	Var B+C	grism 4	2700	Ekar
Dec. 08, 2004	Var B+C	U image	900	Ekar
Dec. 08, 2004	Var A	grism 4	3000	Ekar
Dec. 08, 2004	Var A	V image	300	Ekar
Dec. 08, 2004	Var A	B image	600	Ekar
Jan. 13, 2005	GR 290	grism 7	3000	Loiano
Jan. 16, 2005	Var C	grism 4	1500	Loiano
Sep. 05, 2005	Var B	grism 4	3000	Loiano
Sep. 27, 2005	Var A	B images	2×600	Loiano ²
Sep. 27, 2005	Var A	V images	2×240	Loiano ²
Sep. 27, 2005	Var B+C	B images	2×600	Loiano ²
Sep. 27, 2005	Var B+C	V images	2×240	Loiano ²

¹ Published in Polcaro et al (2003); ² also $B - V$ images of an intermediate field.

to a change in seeing conditions, or to both. The spectrum of Var A reported in Figs. 1 and 4 has been corrected of this factor. Generally, we have found good agreement between the observed $B - V$ colour indices and those derived from the spectral energy distribution. While one needs to be careful with the derived absolute fluxes of course, but the relative flux calibration is quite reliable, with the exclusion of the wavelength range below ~ 3900 Å. Finally, in Fig. 1 it is also clear that several small features are equally present in both spectrograms of GR 290, Var B, and Var C, which confirms that they are real spectral features, in agreement with the high S/N of these spectra. As discussed below, this result is particularly important in the case of Var C, whose spectrum is found to be dominated by a large number of ionized iron emission lines, which at our resolution are mostly seen as unresolved blends. Figure 2 shows the spectrum of the three LBVs and of UIT 3 normalized to the continuum.

The photometric observations of GR 290 were reduced using the secondary standard stars listed in Table 2. Details are given in the table caption, where R and I are defined according to the Cousins systems. Table 3 gives the photometric observations of GR 290 collected during 2003–2005 at the Asiago, Greve, and Loiano Observatories. The table also gives the revised BVR values of GR 290 of February 2003, obtained using the new standards given in Table 2.

¹ J2000 coordinates of the target stars: GR 290: $\alpha = 01^{\text{h}}35^{\text{m}}09.71^{\text{s}}$, $\delta = +30^{\circ}41'57.1''$; Var A ([HS53] A): $\alpha = 01^{\text{h}}32^{\text{m}}32.52^{\text{s}}$, $\delta = +30^{\circ}30'22.4''$; Var B ([HS53] B): $\alpha = 01^{\text{h}}33^{\text{m}}49.23^{\text{s}}$, $\delta = +30^{\circ}38'09.1''$; Var C ([HS53] C): $\alpha = 01^{\text{h}}33^{\text{m}}35.12^{\text{s}}$, $\delta = +30^{\circ}36'00.4''$; UIT3 ([MBH96] 3): $\alpha = 01^{\text{h}}32^{\text{m}}37.70^{\text{s}}$, $\delta = +30^{\circ}40'05.7''$.

² IRAF is distributed by the NOAO, which is operated by AURA under contract with NSF.

Table 3. Multicolour photometry of GR 290¹.

Date	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>	Notes
Feb. 02, 2003		17.77 ± 0.20	17.70 ± 0.15	17.69 ± 0.10		Loiano ²
Dec. 20, 2003				17.37 ± 0.11		Greve
Jan. 15, 2004		17.37 ± 0.07		17.34 ± 0.08		Greve
Jan. 21, 2004		17.54 ± 0.08	17.62 ± 0.08			Greve
Feb. 15, 2004		17.40 ± 0.15	17.56 ± 0.05	17.35 ± 0.05		Asiago
Oct. 10, 2004			17.15 ± 0.06	16.90 ± 0.08		Greve
Dec. 6-7, 2004	16.22 ± 0.06	17.09 ± 0.04	17.18 ± 0.03	16.94 ± 0.05	16.93 ± 0.03	Asiago
Jan. 01, 2005				17.05 ± 0.07	17.54 ± 0.24	Greve
Jan. 05, 2005			17.36 ± 0.06	17.06 ± 0.07	17.34 ± 0.26	Greve
Jan. 07, 2005				17.02 ± 0.05		Greve
Jan. 30, 2005		17.07 ± 0.05				Greve
Feb. 02, 2005		17.13 ± 0.08	17.24 ± 0.07			Greve
Feb. 03, 2005			17.29 ± 0.10	17.09 ± 0.08		Greve

¹ All the Greve measurements are a mean of typically 3 to 5 exposures. ² Polcaro et al. (2003) improved values.

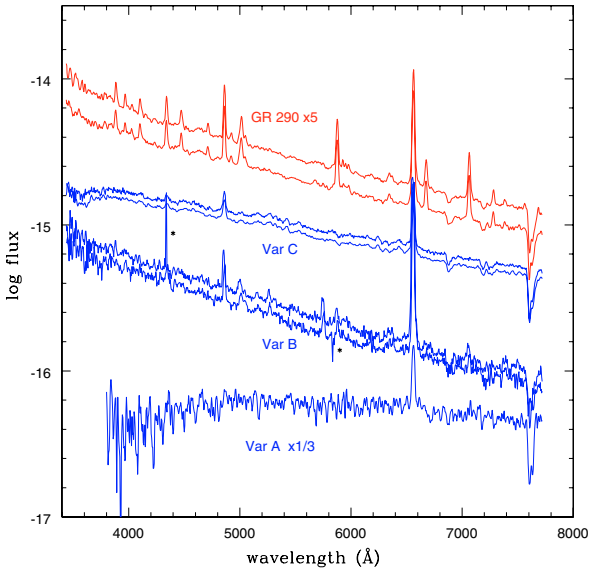


Fig. 1. The December 2004 low resolution spectrograms of the four luminous variable stars in M 33. From the bottom: the Hubble-Sandage variables A, B, C, and the Romano’s star GR 290. For three stars two individual spectrograms taken at different times (see Table 1) are shown. Ordinates are log fluxes in cgs units with a vertical shift for GR 290 and Var A. Spectral artifacts are marked with an asterisk.

For the photometry of the field of Var A, we obtained a calibration curve using the photoelectric standards listed by Sandage & Johnson (1974). The photometry of blue and red supergiant stars in the field was used to derive a conversion factor of the photoelectric magnitudes into the modern photometric system³. For the photometry of the *B* and *V* images of Var B and Var C, we have used the already calibrated fields of Var A and of GR 290, whose calibration was transposed to the field of Var B and Var C using intermediate regions. The *U* image of Var B and C was

³ In the calibration diagrams we found for the *B* and *V* magnitudes reported by Ivanov et al. (1993) a dispersion larger than for those of Sandage & Johnson (1974). This can be attributed either to a photometric variability of the Ivanov et al. stars and/or to their larger measurement errors. We also note that in SIMBAD the star IFM-B33a of the Ivanov et al. catalogue has the same coordinates as the Sandage-Johnson standard A14, which is one magnitude brighter, and we have found that the last value is the right one.

calibrated mostly using the *U* mag from the UIT sources of Massey et al. (1996). This photometry has a lower accuracy.

4. The Hubble-Sandage variable A

Using the procedure described above we find for Var A: $B = 19.5 \pm 0.1$ and $V = 18.6 \pm 0.1$ (December 2004) and $B = 19.6 \pm 0.1$ and $V = 18.7 \pm 0.2$ (September 2005). Presently the star is brighter in *B* than during 1982–1990 (Kurtev et al. 2001), while the *V* luminosity is close to that recorded during 1977–1986 when Var A was at a minimum (Humphreys et al. 1987). In December 2004 the spectrum shown in Fig. 3 presents $H\alpha$ prominent in emission with $W_{\text{eq}} = 35 \pm 5 \text{ \AA}$ and $H\beta$ marginally visible. No other emission lines can be identified unambiguously. The not-dereddened energy distribution is flat with a decreasing trend for wavelengths shorter than about 4500/4300 \AA . The slope of the spectrum in the blue-visual (which corresponds to a $B - V$ of about +0.87) agrees with the measured colour index of $B - V = +0.9$. If we take a value of $A_V \sim 0.7$ for the visual interstellar extinction, as suggested by Humphreys et al. (1987), we derive for Var A a dereddened colour index typical of an A–F spectral type. This A_V value was used to produce the dereddened spectrum of Var A plotted in Fig. 3, where it is compared with the spectra of standard supergiant stars of different spectral types. The figure indicates a good agreement between the energy distribution of Var A and that of late F–supergiants (from Jacoby et al. 1984). In the present spectrum of Var A, one can, on the other hand, identify some photospheric lines typical of G–K spectral types. These are the Ca II h and k doublet, Ca I 4226 \AA , the g band at 4310 \AA , the Mg I b band at 5180 \AA , and probably the CN line at 3880 \AA . The strength of these lines would suggest a more advanced spectral type than we derived from the dereddened SED. Even by decreasing the reddening, this discrepancy has not been solved. Humphreys et al. (1987) have noticed a similar discrepancy between the spectrum and the photometric colours, which they attribute to the scattering (and blueing) of the stellar radiation by a possibly bipolar reflection nebosity.

Finally, one can notice in the December 2004 spectrum of Var A the complete absence of the TiO bands observed by Humphreys et al. in 1986–87. If present, these bands would be clearly detected in our spectrum of Var A, as they are in the spectrum of the much fainter M-type star M33a–460 near GR 290 ($V = 19.30$; Massey 1998), shown in Fig. 3.

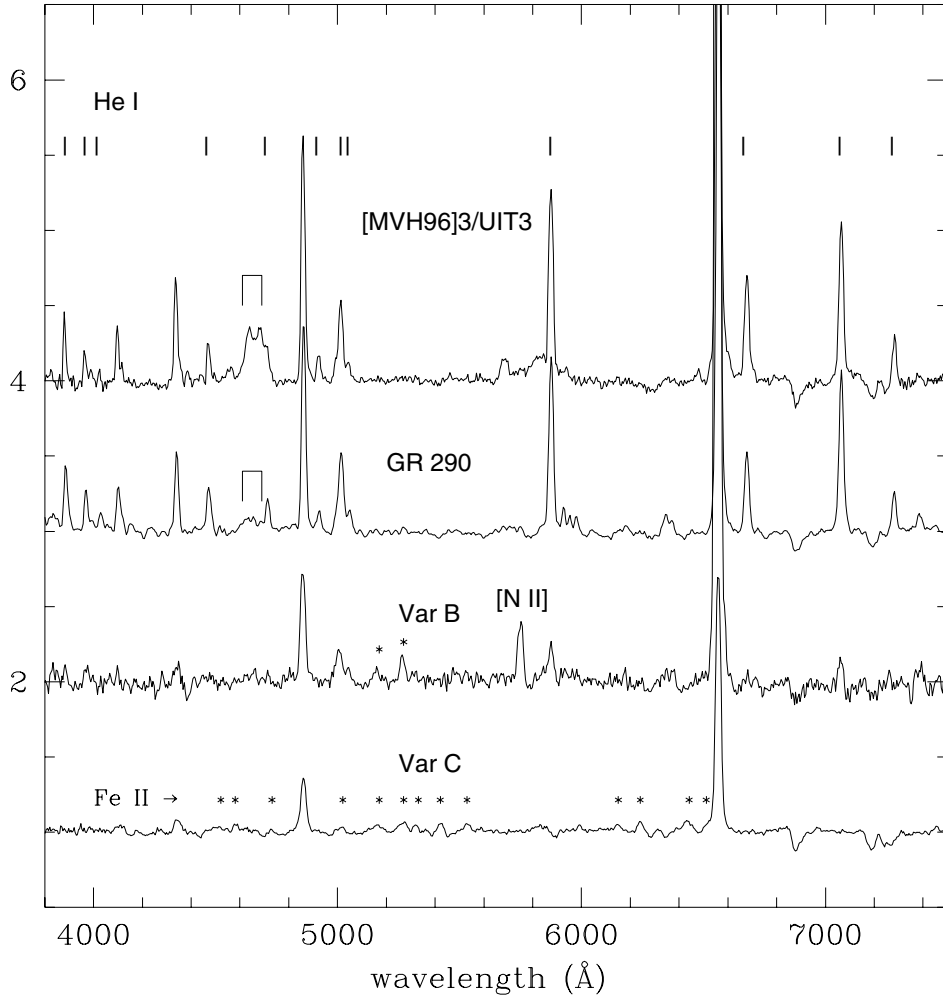


Fig. 2. Cima Ekar spectrograms of the LBVs Var C, Var B, and GR 290, and of the Ofpe/WN9 star UIT3 in M 33. Ordinates are fluxes normalized to the continuum, with offsets for Var B, GR 290, and UIT3. For the LBV stars, we used the combination of two spectra, taking away the artifacts. Some line identification is given (see also Figs. 5 and 6). The 4600–4686 Å feature in UIT3 and GR 290 is indicated. The wavelength position of the He I and Fe II emission lines is marked with vertical bars and stars, respectively.

4.1. The puzzling nature of Var A

Variable A has documented variations in both its luminosity and spectral type (see Hubble & Sandage 1953; Rosino & Bianchini 1973; Humphreys et al. 1987; Kurtev et al. 2001). In 1950 Var A underwent a brightening of ~ 1.5 (photographic) magnitudes. At this epoch a spectrum similar to an F0 type was observed with $H\beta$ in weak emission and H absorption lines weaker than in a standard F0 due to filling-in emission (Hubble & Sandage 1953). In 1951, the star decreased by about 4 mag from the 1950 maximum and brightened again shortly in 1952. In 1953 it decreased to below the minimum of 1951. During 1977–1986, Var A was always around minimum brightness, and $H\alpha$ was observed to be weak in emission at these times (Humphreys et al. 1987). Kurtev et al. (2001) found the star at a minimum in B during 1982–1990. The December 2004 spectrum of Var A is very similar to the one observed in the 1940s and 1950s. Then, however, the star was 20 times brighter in the visual, namely an intermediate $\sim G$ type with H lines in emission. There is no evidence of the M spectral signatures observed 20 yr ago, although the visual magnitudes are comparable. The spectral evolution is also marked by the $B - V$ colour index, which is now 0.7 mag bluer. The $H\alpha$ emission is, on the other hand, much stronger. This line is probably formed in a collisionally-excited expanding envelope or wind.

Its strengthening since the 80s possibly reflects an increase in the mass loss rate from the star.

Humphreys et al. (1987) discussed the optical-infrared energy spectrum of Var A, and found a strong 370 K mid-infrared emission that they attribute to the presence of an opaque dusty envelope surrounding the star and largely absorbing its optical photons, as is the present case for the galactic LBV η Car. The corresponding infrared bolometric magnitude of -10.1 (the value of Humphreys et al. has been adapted to the different M 33 distance scale used in this work) should represent the intrinsic luminosity of Var A that, without the dust envelope, would have been ~ 3 mag brighter in V .

We cannot guess the present bolometric luminosity of Var A, since there are no infrared observations close to our observations. However, the star is present in the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003), which provides the following infrared broadband values $J = 16.89 \pm 0.14$, $H = 15.89 \pm 0.16$, and $K = 14.79 \pm 0.09$, referred to as 1997 December 5. These JHK measurements are about 0.4 mag fainter than in 1980–1986, as reported by Humphreys et al. (1987). Both data sets, corrected for the interstellar extinction of $A_V = 0.7$ derived by Humphreys et al. (1987), are shown in Fig. 4, where we also present the optical energy distribution of Var A as derived from our December 2004 observations.

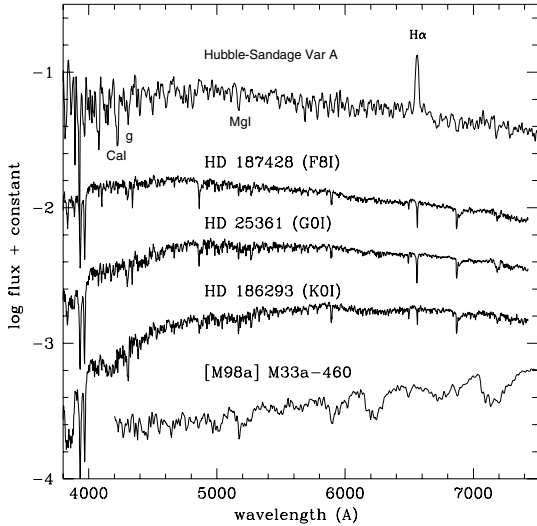


Fig. 3. Comparison of the Hubble-Sandage Var A spectrum with that of three standard supergiant stars. The Var A spectrum has been corrected for $A_V = 0.7$. The Asiago not dereddened spectrum of the M-type star M33a-460 (Massey 1998) is also shown. Ordinates are Log fluxes plus a constant.

If we conservatively take the lower 2MASS observations for the present SED of Var A, the optical-near IR energy distribution can be fitted with two black-body curves with temperatures of 6500 K and 1350 K. The rather high temperature of the optical component is in line with the discrepancy discussed above between the stellar colour index and the spectral features. The bolometric magnitude of this “stellar” component is -7.2 , corresponding to a luminosity of $\sim 6 \times 10^4 L_\odot$. Most probably, Var A still is largely obscured by the cold dust envelope found by Humphreys et al.; in this regard, it would be important to have new mid-IR observations to look for any structural evolution of this cold envelope, in particular whether the dust that is probably formed after the 1950 maximum is now dissipating. As for the near-IR component at 1350 K it could be emitted by hotter dust belonging to an envelope closer to the star, possibly an equatorial disk heated by the stellar radiation.

5. The Hubble-Sandage Var B

The December 2004 spectrum of Var B (IFM-B 1003 in Ivanov et al. 1993) displays the strongest $H\alpha$ emission line ($W_{\text{eq}} = -310 \text{ \AA}$) in our sample. The not-dereddened energy distribution of Var B is visible in Fig. 1. It is quite steep, indicating that the star was in a “hot phase” at the moment of our observations. The same spectrum, normalized to the continuum, is shown in Fig. 2. At this resolution there are no clear photospheric absorption lines, that are probably filled-in by the strong emission components. Many He I lines are present in emission, while the large $H\alpha/H\beta$ flux ratio suggests collisional excitation of the hydrogen lines. Additionally, several emission lines of N II can be identified. Of particular interest is the presence of the [N II] 5755 Å auroral line. The nebular [N II] 6584 Å line is marginally visible in the red wing of the $H\alpha$ line. We have also found two emissions at 5169 Å and 5275 Å, which are identified to two strong Fe II line blends, and the Na I yellow doublet in absorption, clearly of interstellar origin.

At the time of our spectroscopic observations, December 2004, the photometric data of Var B, derived as discussed in Sect. 2, were: $U = 16.3 \pm 0.3$, $B = 17.4 \pm 0.1$ and $V = 17.5 \pm 0.1$,

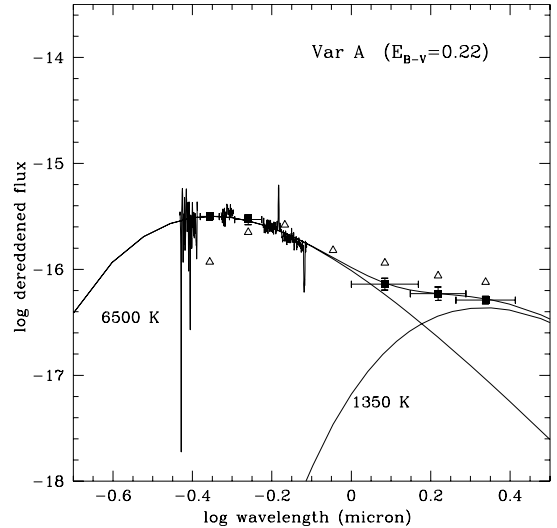


Fig. 4. The energy distribution of Var A. Both the B and V photometric observations and the calibrated spectrum are shown. For better clarity on the plot, the spectral portions inside the B and V bands have been cut. The 2MASS JHK photometry, referred to December 1997, is also reported. Ordinates are log fluxes (in $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$) corrected for an $E_{B-V} = 0.22$. A correction factor has been applied to the spectrum in order to fit with the $B V$ mag. The optical-near IR energy distribution is fitted by a combination of 6500 K and 1350 K black body spectra. The optical-near IR photometric data from Humphreys et al. (1987) are shown for comparison (open triangles).

and for September 2005 we have found $B = 17.5 \pm 0.1$ and $V = 17.6 \pm 0.1$. As discussed above, the U value is fairly uncertain. The $B - V$ and, to a lesser extent $U - B$, colour indices confirm that the star is presently in a hot phase. Both the colour indices and the continuum slope correspond to that of a slightly reddened early B-type supergiant star.

5.1. Discussion

The historical light curve of Var B was described, among others by Hubble & Sandage (1953), Rosino & Bianchini (1973), and Sharov (1973, 1975). The star underwent ample secular light variation between ~ 17 and ~ 14.5 (photographic magnitudes). Hubble & Sandage (1953) report a blue colour index ($CI = -0.3$) in mid 1952 when the star was faint ($m_{\text{pg}} = 16.5$). A “slightly negative” CI was also found by Rosino & Bianchini (1973) in 1962 during rising ($m_{\text{pg}} = 15.5$). Szeifert et al. (1996) and Kurtev et al. (2001) report a gradual brightening of Var B from $B \simeq 17.8$ in 1982 to ~ 16.8 in 1983 and to ~ 15.0 in 1992.

The spectrum of Var B observed near maximum in 1950 (Hubble & Sandage 1953) and towards the end of 1952 (Szeifert et al. 1996; see also Massey et al. 1996) was showing signatures of an F-supergiant type with hydrogen lines in emission. Szeifert et al. describe the HST-FOS UV spectrum obtained in December 1992 ($V = 15.0$) as dominated by emission and absorption lines of ionized iron. They also report the existence of a strong near-infrared emission ($K = 13.9$) and fitted the optical-IR energy distribution with a 9000 K blackbody, assuming an interstellar extinction of $A_V = 0.7$, while the distribution in the UV spectral range falls below the extrapolated blackbody spectrum, most probably due to the strong UV-line blocking by ionized iron. In the more recent 2MASS photometry of Cutri et al. (2003), Var B is bright in the IR, although slightly fainter than in 1992. The

2MASS photometry is referred in December 1997 when the star was probably near visual maximum.

Presently, Var B has a optical luminosity close to the minimum values of its historical light curve. Indeed, its present spectrum is typical of the “hot phase” of LBVs when they are near minimum. The present colour index $B - V$ of about -0.15 would put an upper limit to the interstellar extinction, which should be around $E_{B-V} = 0.10/0.15$, lower than was adopted by Szeifert et al. (1996). If we use this value and neglect the contribution of any infrared excess, assuming the same bolometric correction of an early B-type supergiant, we derive an absolute bolometric magnitude of about -9.7 , corresponding to a bolometric luminosity of $5.9 \times 10^5 L_{\odot}$. This luminosity should be considered as a lower limit, if Var B still has an infrared excess strong enough to contribute.

The strength of the He I emission lines and the prominent $H\alpha$ emission indicate the presence of a strong flux of UV photons. The 4650 \AA emission feature is absent, but N II is present in emission. In general the spectrum resembles that of P Cyg or that of AG Car in transition between minimum and maximum.

6. The Hubble-Sandage Var C

The spectrum Var C (IFM-B 600) has received a large but discontinuous attention since the early Hubble & Sandage (1953) discovery. The first spectroscopic observations were made by Hubble & Sandage themselves who found something near the 1950 maximum $H\beta$ and He I lines in emission, while the Ca II doublet was present in absorption. Sharov et al. (1975) reported a strong $H\alpha$ emission in 1973 when Var C was near minimum. As for the 1983–90 maximum, Kenyon & Gallagher (1985) identified hydrogen and weak ionized iron emission lines in their 1983 spectrum, while Humphreys et al. (1988) observed an absorption spectrum typical of that of early F (1985) and A-type (1986) supergiants. The most recent spectra have been described by Szeifert et al. (1996) when the star was in eruptive phase (1987, 91, 92), and they report the presence of several weak emission lines from ionised iron. They also describe the UV (HST-FOS) spectrum of the star, which is dominated by absorption and emission lines of ionized iron.

In December 2004, the spectrum of Var C presented numerous emission features presumably from blended singly ionized iron lines, besides $H\alpha$ and $H\beta$ strong in emission ($W_{\text{eq}} = -49$ and -11 \AA , respectively). Due to the large number of individual lines that can contribute to a single emission feature, a correct identification is possible only by comparing with the low-resolution spectrum of an “Fe II emission line star” whose spectrum has been well-identified at high resolution. To attempt an identification of these features, we compared this spectrum with a low-resolution spectrum of the B[e] star HD 45677, which presents this kind of Fe II emission lines. We obtained such a spectrum at Asiago with the same instrumental setup as was used for Var C’s spectrum. The line identification of HD 45677 was kindly provided to us by Gerard Muratorio (see Muratorio et al. 2006). As can be seen in Fig. 5, there are several line structures in common between Var C and HD 45677 spectra, most of which coincident with permitted and forbidden ionized iron lines. Particularly prominent in the wavelength range between $H\beta$ and $H\alpha$ are the Fe II lines of multiplets 42, 49, and 74. The 6300 \AA line of [O I] is also present. We identify the peak at 5530 \AA with the [Fe II] $\lambda 5527.33$ line and the absorption at 5900 \AA with the Na I interstellar doublet. At our resolution the Balmer series is in emission up to at least H8. In general, the present spectrum resembles the

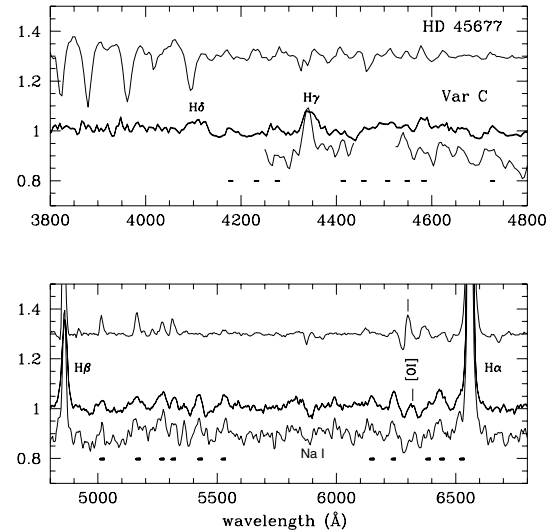


Fig. 5. Comparison of the Loiano (*bottom*) and Asiago (*middle*) spectra of Var C with that of the B[e] star HD 45677 (FS CMA, *top*). The Asiago spectrum is the combination of the two December 2004 observations. Ordinates are fluxes normalized to the continuum, with an offset of $+0.3$ for HD 45677 and of -0.1 for the Loiano spectrum of Var C. The main Fe II and [Fe II] emission lines or blends identified in Var C are marked below the spectrum.

one previously observed out of the bright phases and at minimum light. The mean excitation level of the emission lines suggests a temperature for the emitting envelope similar to that of B[e] supergiant stars.

For the photometry of Var C we have derived the following values: $B = 16.5 \pm 0.2$, $V = 16.4 \pm 0.2$ for December 2004, and $B = 16.6 \pm 0.1$, $V = 16.6 \pm 0.1$ for September 2005. The 2004 photometric data agree fairly well with the magnitudes derived from the better exposed spectrum (upper spectrogram of Var C in Fig. 1). The U magnitude was found to be quite bright (15.3 ± 0.3) with respect to that expected from the spectrum. This anomaly could be due, at least partly, to a blend of the LBV star with a UV-bright nearby star. In this regard, Szeifert et al. (1996) had noticed from HST-Faint Object Camera observations of March 1993 the presence of two stars near Var C, one ~ 1 arcsec to the West and another fainter one at about 2 arcsec to the North, one of which was of comparable brightness to Var C at 2000 \AA . In the present luminosity phase of Var C, these UV object(s) should probably give a small contribution to the V and B bands, but a much larger contribution to the U -band⁴. Clearly, this is a point that deserves future multiband observations with higher spatial resolution.

6.1. Discussion

Variable C has a light variability history that indicates repeated phases of variability with minima around $V = 17$ and maxima that are about two magnitudes brighter (see, e.g. Hubble & Sandage 1953; Rosino & Bianchini 1973). In recent years it has been around minimum luminosity ($V \sim 17$) up to 1982, since when the star started a luminosity increase up to magnitude 15th, and a subsequent fading down to the 16th magnitude (Szeifert et al. 1996; Kurtev et al. 2001). In the infrared, Szeifert et al. report the following broad-band magnitudes $J = 15.64 \pm .04$,

⁴ In our B and V observations the images of Var C are elongated to the West due to the presence of a much fainter, and probably redder, star separated by about 2 arcsec, whose contribution to the B and V mag of Var C is small.

$H = 15.52 \pm .07$, $K = 15.28 \pm .07$ referring to 1992. The optical-infrared distribution derived by these authors was fitted by a 15 000 K blackbody, assuming $A_V = 0.8$. As in the case of Var B, the UV spectrum of Var C lies below the fitted black-body distribution due to the strong and non-uniform line blocking by the Fe II lines. In general, the long-term spectral and photometric history of Var C seems to have followed the typical behaviour of S Dor variables, with the emission lines becoming weaker near maximum when an intermediate-type absorption spectrum emerges. At present, Var C is dimmer than at the time of the last reported spectroscopic observations of 1992, but the spectrum looks very similar with a forest of Fe II lines, showing it to be in what we could call an η Car-like phase. The weaker infrared emission, which can be derived from the 2MASS catalogue survey of December 1997 ($J = 16.55 \pm 0.12$, $H = 16.25 \pm 0.22$, and $K = 15.71 \pm 0.20$), shows that also in the infrared the star was in a phase of decreasing luminosity, at least during 1992–97.

If we assume that the present visual and blue magnitudes can be attributed almost in its entirety to Var C, notwithstanding the presence of the nearby objects described above, and neglect the contribution of any infrared excess, we derive a bolometric magnitude of about -10.0 , having assumed a bolometric correction of about -1.0 , as appropriate for an intermediate B-type supergiant, and an extinction of $A_V = 0.6$, in agreement with the present $B - V$ colour. From this we derive a luminosity of $0.79 \times 10^6 L_\odot$ similar to that of Var B. As in the case of Var B, here we have neglected the contribution of a possible infrared excess, although it might be small, as suggested by the marked decrease in the IR emission observed with 2MASS.

7. The Romano's star GR 290

The spectrum of Romano's star GR 290 has been described in detail by Polcaro et al. (2003), who confirmed its S Dor nature and pointed out the presence of the 4630–60 Å blend and weak He II 4686 Å in emission, which is a typical feature of Of stars, and a similarity to the spectrum of the galactic LBV AG Car during its hot phases, as described by Stahl (1986) and Viotti et al. (1993). The December 2004 spectrum is shown in Fig. 6. Besides the Balmer lines, the spectrum is very rich in emission lines of neutral helium. Several N II lines are also present in emission. Of particular interest is the region near 4650–4700 Å characterised by a shallow emission, extending redwards from about 4600 Å till the prominent He I 4713 Å emission line. The broad emission is a blend of N II and N III lines and of He II 4686 Å. This is a characteristic spectroscopic feature of the intermediate category of Of/WN stars (Walborn 1982). The peak of the [N II] 6584 Å emission line is clearly visible in the grism 7 spectrum of January 2005 (see Fig. 6); in the other spectrograms, the line is present as an enhancement of the red wing of H α .

In order to assess GR 290's connection with the O-type emission line stars, we compare in Fig. 6 the spectrum of GR 290 with the Cima Ekar spectrum of the Ofpe/WN9 star UIT3 in M 33 discussed by Bianchi et al. (2004). Differences and similarities are evident in the figure. The most evident difference is the 4600–4686 Å emission, which is much stronger in UIT3 than in GR 290. In particular the He II 4686 Å line is present in UIT3 at a 35% level above the continuum. The second peak at 4640 Å is attributable to the N III multiplet 2 fluorescence lines. In GR 290 the 4650 Å emission band is mainly composed of the N II multiplet 5 lines, with probably a lesser contribution from N III, while He II is marginally visible. An interesting aspect

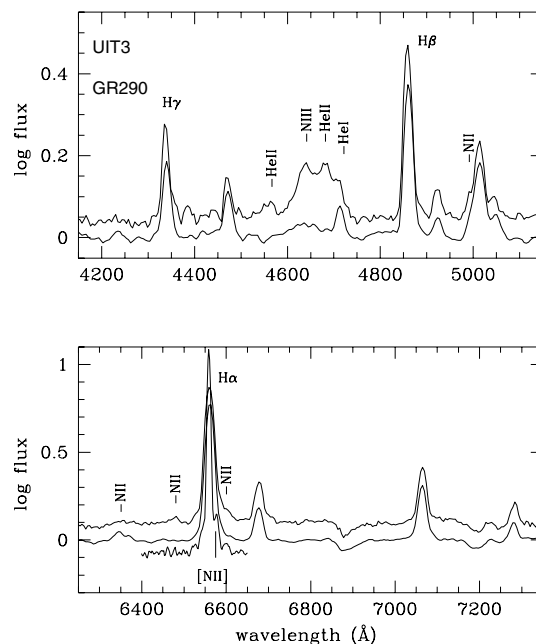


Fig. 6. Comparison of the December 2004 spectra of GR 290 and UIT3. Ordinates are Log fluxes normalized to the continuum, with a slight upward offset for UIT3. Some line identification is indicated. Note the nearly equal strength of the hydrogen and He I emission lines in GR 290 and UIT3. A portion of the January 2005 grism 7 spectrum of GR 290 is also plotted below the December 2004 spectrum to show the [N II] 6584 Å and N II 6610 Å lines in the red wing of H α .

of the spectrum of GR 290 and UIT3 is that, in spite of the differences mentioned above, *all the hydrogen and neutral helium lines have nearly the same strength with respect to the underlying continuum.*

The relative strength of the He II line and of the singly and doubly ionized nitrogen suggests a later spectral type for GR 290 than for UIT3, closer to the WN11 type introduced by Smith et al. (1994). Indeed, the spectrum of GR 290 resembles that of the Ofpe/WN9 (WN11) star in NGC 300 described by Bresolin et al. (2002). We note that in GR 290 the emission lines appear narrow within the spectral resolution. For the spectral behaviour, the spectrum of GR 290 was observed at five different epochs between February 2003 and January 2005. Some spectra are presented in Fig. 7. Although the 4600–4686 Å feature is always present, it does seem that the feature and, in particular, the He II 4686 Å line have decreased compared with the other lines. The H α line intensity increased in December 2004 and then again in January 2005. The emission equivalent widths of the H β and the He I lines have instead remained unchanged over these two years.

The photometric observations of GR 290 are summarised in Table 3. In Fig. 8 we show the BVR light curve of GR 290, obtained from the multiband photometry during 2003–2005. A brightening of about $-0^m.7$ for GR 290 is noticeable in every band between early 2003 and late 2004. More recently a slight fading has occurred. As discussed above, these variations have occurred without significant spectral variations. In December 2004 we obtained a full set of $UBVRI$ photometry for GR 290. This is the first broad-range multicolour observation of the star. The derived colour indices of $U - B = -0.87$ and $B - V = -0.09$ are typical of a slightly reddened blue star. We also notice, incidentally, that the colour indices of GR 290 are quite similar to

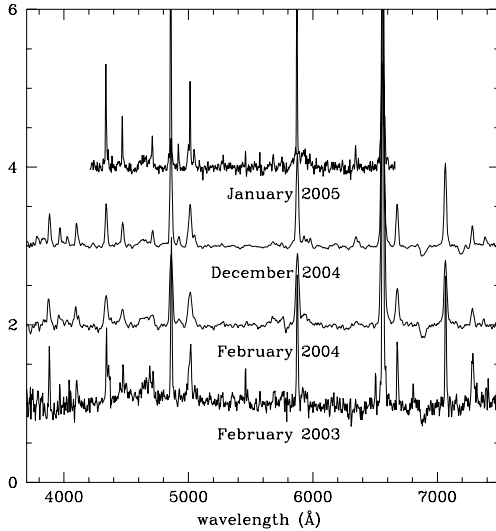


Fig. 7. The spectrum of GR 290 taken at different epochs during 2003–2005. From bottom to top: 2 February 2003, 14 February 2004, 6 December 2004, 16 January 2005. Ordinates are fluxes normalized to the continuum, with vertical offsets.

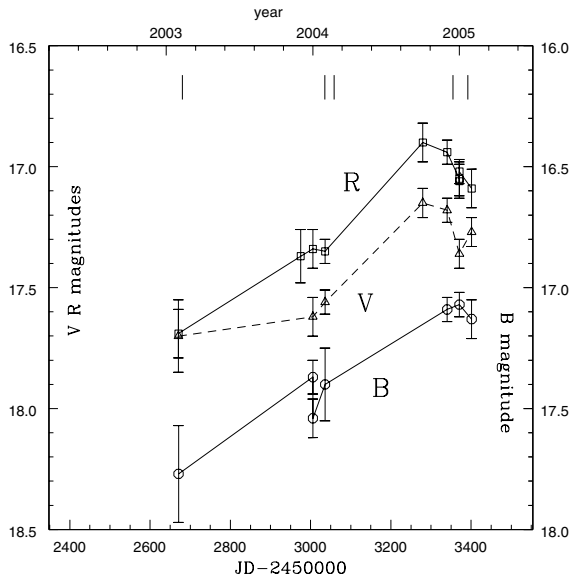


Fig. 8. The multifrequency (B : circles, V : triangles, R : squares) light curve of GR 290 during 2003–2005. The vertical bars at the top of the figure indicate when spectroscopic observations were made.

those derived for Var B ($B - V = +0.01$ and $U - B = -1.03$) and to those of UIT3 ($B - V = +0.01$ and $U - B = -0.98$, Bianchi et al. 2004). Actually, it is also evident from Fig. 1 that the non-reddened SEDs slopes of GR 290 and Var B are very similar. Of course a more precise comparison should take into account the interstellar reddening which is not well known; it cannot easily be determined from the energy distribution because this is not very likely a standard distribution for a hot star, due to the presence of a hot envelope where the emission line spectrum is formed. One possibility would be to estimate the interstellar reddening from neighbouring stars in M 33. The two young stellar clusters, OB 89 and OB 88, are located 1 to 3 arcmin to the west of GR 290. According to Massey et al. (1995), both these associations are not very reddened with $E_{B-V} = 0.17 \pm 0.07$ and 0.15 ± 0.04 for OB 89 and OB 88, respectively. If we assume an average reddening value E_{B-V} (0.16) we find that, adopting

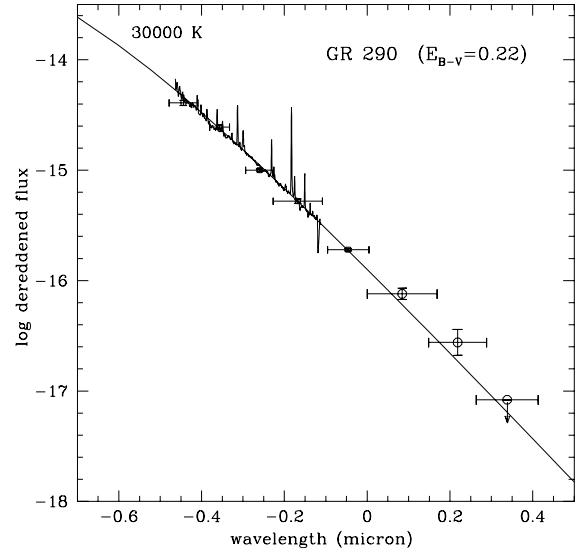


Fig. 9. The energy distribution of GR 290. Both the December 2004 $UBVRI$ photometric observations (squares with error bars) and the calibrated spectrum (the upper spectrogram in Fig. 1) are shown. The 2MASS JH photometry and the K upper flux limit, referred to as December 1997, are also reported (circles). Ordinates are log fluxes (in $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$) corrected for an $E_{B-V} = 0.22$. The 30 000 K black body distribution normalized to the visual is shown for comparison.

the galactic reddening law, the dereddened 5-colour photometry and spectral distribution are best fitted by a 20 000 K black-body energy spectrum. However, this temperature is too low for GR 290's spectral type. A more reasonable estimate is probably obtained with a black-body distribution of 30 000 K, if we take a higher reddening value between 0.20 and 0.24. In Fig. 9 we show the energy distribution of GR 290 obtained assuming this latter temperature and a reddening of $E_{B-V} = 0.22$. With this assumption the intrinsic colour indices of GR 290 are $U - B = -1.03$ and $B - V = -0.31$, which are consistent with those of a late-O type supergiant star.

It would be interesting to know the behaviour of the SED of GR 290 in the infrared. The 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003) gives HJK data for this star, referred to 5 December 1997: $J = 16.83 \pm 0.13$, $H = 16.70 \pm 0.29$. For K there is only a magnitude lower limit of 17.76. No optical observations exist to our knowledge in the literature for this epoch. Nonetheless, the closeness of our I magnitude and of the 2MASS J value, along with the contiguity between the optical and infrared distributions, as illustrated in Fig. 9, indicate that GR 290 probably had a similar luminosity in 1997. In Fig. 9, one can also notice a marginal IR excess that could indicate a free-free emission. But more infrared and coordinated optical observations are needed to fully assess that.

7.1. Discussion

If for GR 290 we adopt an interstellar extinction of $E_{B-V} = 0.22 \pm 0.02$ and the bolometric correction of an O9 supergiant, we obtain an absolute bolometric magnitude of -11.5 ± 0.1 for GR 290 in December 2004, corresponding to quite a high bolometric luminosity of $3.2 \times 10^6 L_{\odot}$. This luminosity can be compared with that of members of the nearby OB 88 and OB 89 clusters. Using the photometric observations of Ivanov et al. (1993) and Massey et al. (1995), we find that, if GR 290 were associated with those clusters, it would be the most luminous star of the system, a point

Table 4. Derived stellar parameters (December 2004).

star	spectrum	H α ¹	V	B – V	A _V	T (K)	B.C. ²	M _{bol} ³	log L/L _⊙	phase ⁴
GR290	Oe (WN11)	–120	17.18	–0.09	0.68	30 000	–3.2	–11.5	6.5	min
Var A	F–G	–35	18.60	+0.88	(0.7)	6 500	–0.3	–7.2 ⁵	4.8	min
Var B	Be	–310	17.50	–0.15	0.37		–2.0	–9.7	5.8	min
Var C	B[e]	–49	16.40	+0.10	0.6		–1.0	–10.0	5.9	post max

¹ Equivalent width of the H α emission line in Å. ² Adopted bolometric correction. See A. N. Cox, *Allen’s Astrophysical Quantities* (2000). ³ Assuming for M 33 $m - M = 24.8$ (Kim et al. 2002). ⁴ Photometric phase. ⁵ Value referred to the optical spectral component (Fig. 4). The star should be subject to a $\sim 3^m$ obscuration in the visual due to the presence of a dusty envelope that is responsible for the strong mid-infrared emission found by Humphreys et al. (1987).

that is not very surprising in view of its spectral peculiarities. At any rate, it would be important to assess the membership of GR 290 with any of these associations, although its vicinity to OB 89 would suggest the latter is the most likely parent cluster.

The recent multicolour light curve of GR 290 shown in Fig. 8 is different from the classical S Dor behaviour, where a decrease in V mag is exhibited for a variation in colour index towards the blue, while this was not the case of GR 290 during 2003–2004. Other kinds of variability, non S Dor-type, could of course have taken place (see van Genderen 2001). Recently, Fabrika et al. (2005) describe a 4550–5300 Å spectrum of GR 290 taken in September 1998. Besides H β being strong in emission, the spectrum shows several He I emission lines with P Cygni absorptions blue-shifted by 100–300 km s^{–1}. N II is also weakly visible near 5000 Å. The helium and nitrogen lines appear weaker than in our spectra, probably because at that time the star was slightly cooler (and probably brighter) than at present. An older spectrum of GR 290, obtained in late 1991 when the star was brighter than presently, displayed weak He I and Fe II emissions, and a prominent H α emission with extended wings and a blue-shifted P Cygni absorption (Szeifert 1996). This argues in favour of a recent transition of GR 290 in the H–R diagram towards hotter temperatures.

8. Concluding remarks

We have discussed the present status of four luminous variable stars – three LBVs and one yellow hypergiant – in the nearby galaxy M 33, which are known to have undergone S Dor-type luminosity variations during their historical light curve. Table 4 summarises the stellar parameters we have derived from the December 2004 observations, having assumed the same distance modulus of M 33 given by Kim et al. (2002) for all the stars. The bolometric correction for Var B and Var C is uncertain. In addition, their bolometric luminosity could be a lower limit due to a possible contribution from an infrared excess. In Fig. 10 we show the position of these stars in the H–R diagram and the approximate tracks outlined during their light history, *if the variations occurred at constant luminosity*. GR 290 appears to be the hottest and most luminous of the set and, probably, is one of the brightest LBVs. Some evolutionary tracks of massive stars (from Chieffi & Limongi 2006) are reported in the figure, although one should consider that the evolution of very massive stars is still a matter of discussion. In particular the role of stellar parameters such as chemical composition, rotation, and binarity has not yet been fully understood.

In two stars – the Hubble-Sandage variables Var A and Var B – we have found dramatic differences with respect to the previous observations. Presently both are at visual minimum (with respect to their light history), but Var A has moved from a phase

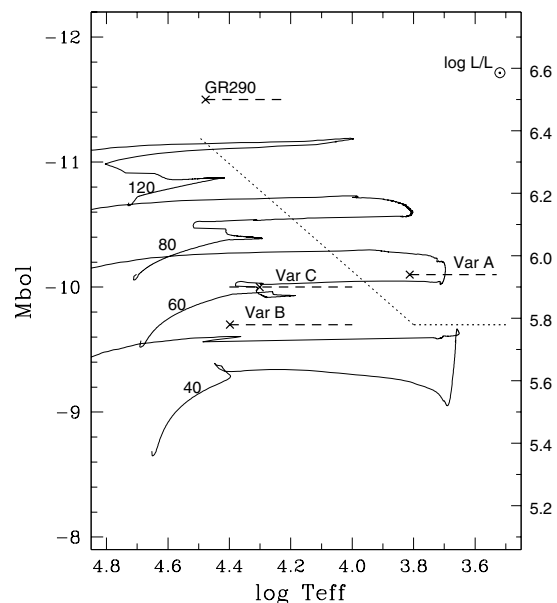


Fig. 10. The H–R diagram showing the location of the 4 studied variables. The dashed lines represent the approximate path covered back and forth by the stars during their light history, assuming constant bolometric luminosity, with the crosses marking their present state (see Table 4). For Var A we used the bolometric magnitude derived by Humphreys et al. (1987) from the IR. The M 33 distance modulus of 24.8 has been assumed for all the stars. The empirical upper luminosity boundary (from Humphreys et al. 1987) is shown as a dotted line. The evolutionary tracks for massive stars with mass loss and solar composition are from Chieffi & Limongi (2006).

dominated by a “pseudo” M-type spectrum to a warmer, G-type. Perhaps, the previous phase was associated to a strong cooling of the dense envelope expelled by the star near (or as a consequence of) the 1950 light maximum. This event was followed by the formation of an extended dusty envelope that is still absorbing most of the stellar visual light. In this regard it is useful to compare the recent behaviour of Var A with that of η Car, which like Var A in 1950–51, has shown a decrease in optical luminosity by many magnitudes in mid-1800 due to the gradual formation of a dust mantel (see e.g., Andriesse et al. 1978; Humphreys & Davidson 1994). Later, η Car displayed an intermediate (F5) supergiant spectrum for a short time. This occurred by the end of the 19th century, when the star underwent a secondary luminosity maximum (see e.g. Viotti 1995). In the following years, the F-type absorptions turned into a forest of prominent emission lines, which still dominate the present spectrum of η Car. The parallel behaviour of Var A in M 33 raises the question of whether Var A presently is in an evolutionary stage in the right

part of the H–R diagram at the red turnover point of the post–MS evolution of 50–70 M_{\odot} stars, or, as in the case of η Car, it is intrinsically a luminous blue variable star that is going through a (long-lasting) transient “cold” phase, probably due to the formation of dense cool shell(s) ejected from the star in historically recent times. If this latter hypothesis is correct, we should expect the appearance of a rich Fe II emission line spectrum in the next years.

The Hubble-Sandage variables B and C probably have similar nature, as indicated by their photometric and spectroscopic history, but presently are in two different stages of their S Dor-type variability: Var B is close to the bluest edge, while Var C is at an η Car-type phase, and probably is going to evolve towards a hotter phase. Var B and Var C probably have close mass and bolometric luminosity.

The similarity between the present spectrum of Var C with that of the B[e] stars also suggests some general considerations about the evolutionary status of the galactic supergiants, showing the so called B[e] phenomenon. There have been suggestions that such B[e] supergiants are quiescent LBVs. That Var C is displaying several, if not all, the features typical of the B[e] spectral class shows first of all that a similar phenomenon is also taking place in the M 33 galaxy, and should support the hypothesis that the B[e] supergiants are in fact connected somehow with the LBV phenomenon.

GR 290 is the most luminous object in our study. In luminosity this star rivals the brightest OB stars in the MW, and should have had quite a high initial mass. Its spectrum has remained close to that of the Of/WN category for at least seven years, but in recent years GR 290 has undergone large photometric changes, substantially without the associated colour variations that are typically observed in LBVs (the S Dor-type variability). The continued photometric activity might be the precursor of a new dramatic evolution of GR 290, marked by the cooling of its atmospheric envelope and by the appearance of a rich Fe II emission line spectrum, like that of η Car.

Finally, the comparison with the Ofpe/WN9 star UIT3, which has a visual luminosity comparable to that of GR 290, brings up an interesting point: the two stars are close in strength of the hydrogen and neutral helium emission lines relative to the continuum. This implies that above a relatively small He^{++} layer, more important in UIT3, both stars have an extended envelope with nearly the same emitting volume. This is an interesting aspect that deserves a thorough spectroscopic investigation at high resolution of a large set of hot emission line stars.

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