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On the population of galactic Luminous Blue Variables

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Abstract. We report the first results of a long term infrared monitoring campaign of known and candidate galactic Luminous Blue Variables (LBVs). In particular, we are able to confirm the LBV nature of G24.73+0.69, a luminous mid-B supergiant associated with a dusty ejection nebula. We find that prior to 2003 September G24.73+0.69 exhibited low amplitude ($\Delta JHK \sim$ 0.4 mag) variability, but in the ~200 day period between 2003 September–2004 April it abruptly brightened by ~0.7 mag in the broadband *J* filter. Subsequently, a further ~0.4 mag increase was observed between 2004 April–October, resulting in an overall difference of ~1.1 mag between (current) photometric mimimum and maximum; similar variability also being observed in the *H* and *K* bands. In light of the numerous recent IR studies of the galactic hot star population we also compile an updated census of confirmed and candidate galactic LBVs, reporting 12 and 23 members respectively for each class. Finally, we utilise this new census to construct an H-R diagram for the galactic LBV population, resulting in a striking confirmation of the LBV-minimum light strip.

Key words. stars: early-type – stars: evolution – stars: supergiants

1. Introduction

Luminous Blue Variables, or S Doradus variables are a class of massive, unstable stars in the upper left of the HR diagram. Defining physical characteristics include a high luminosity and mass loss rate and significant photometric and spectroscopic variability (e.g. the review of Humphreys & Davidson 1994; HD94). Two types of variability may be distinguished; the first occuring at constant bolometric luminosity and reflecting simultaneous cooling (heating) and expansion (contraction) of the star. These changes result in changes in the *visual* magnitude – typically by 1–2 mag – and colours, with the star becoming redder (bluer) as it brightens (fades). This behaviour may also be accompanied by changes in the mass loss rate e.g. AFGL 2298 (Clark et al. 2003a) and NGC 2363-V1 (Drissen et al. 2001). The second form of variability does not conserve the bolometric luminosity of the star and may be accompanied by a significant increase in mass loss rate, which in the case of η Carinae led to the production of the Homunculus ejection nebula. Such giant eruptions appears significantly rarer, with only two examples identified in the galaxy in the past 4 centuries.

The lack of a complete galactic census prevents an accurate determination of the length of the LBV phase and the properties of stars in this unstable regime. Consequently much effort has been expended to identify new LBVs, with IR observations becoming increasingly important in this regard; new candidates having recently been identified via near-IR spectroscopy and/or mid-IR imaging of their circumstellar ejection nebulae.

One such LBV candidate is G24.73+0.69, which Clark et al. (2003b) find to be a luminous ($\log(L/L_\odot) = 5.6$) blue supergiant (T = 12 kK) associated with a dusty ejection nebula. As such it is very similar to AFGL 2298 (=IRAS 18576+0341), which Clark et al. (2003a) demonstrate to be a bona fide LBV on the basis of near-IR spectroscopic and photometric variability.

Consequently, the aim of this manuscript is two-fold; firstly to present the first results of an ongoing photometric monitoring campaign that demonstrate that G24.73+0.69 is indeed an LBV and secondly to present an updated census of galactic LBVs and resultant HR diagram. Given the likelihood that metallicity plays a significant role in the post-Main Sequence evolution of massive stars, compiling a sample of LBVs of ~uniform initial metallicity is a pre-requisite to placing the LBV phenomenon into a wider evolutionary context.

2. Data reduction

Near-IR *JHK* broadband photometric observations of G24.73+0.69 and AFGL 2298 were obtained at the

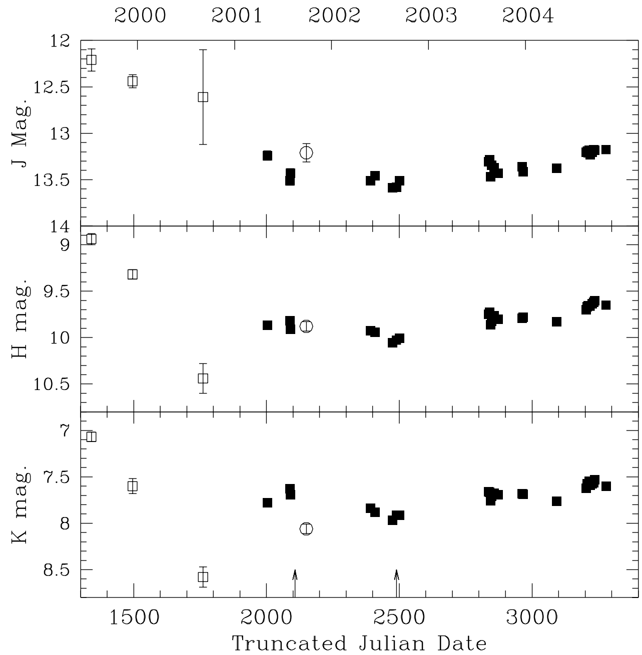

Fig. 1. *JHK* broadband photometry of AFGL 2298. Open squares represent the data of Ueta et al. (2001), circles those of Pasquali & Comeron (2002) and filled squares Clark et al. (2003a) and this work. Errorbars are indicated; for the Campo Imperatore data they are within the size of the symbols. Finally, the two spectroscopic observations from which Clark et al. (2003a) derived physical parameters for the star are indicated by the arrows in the bottom panel.

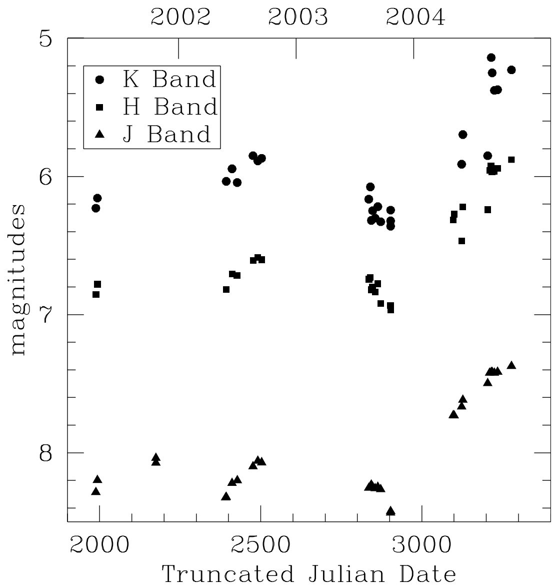

Fig. 2. *JHK* broadband photometry of G24.73+0.69; errorbars are within the size of the symbols.

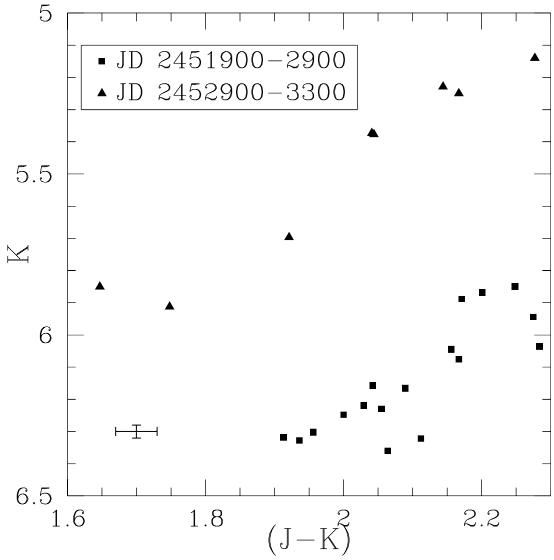

Fig. 3. Colour magnitude plot for G24.73+0.69; we have divided the data into pre- and post-2003 September datasets; the latter dataset apparently after the recent brightening episode. Representative errorbars are presented in the bottom left of the figure.

AZT-24 1.1m telescope in Campo Imperatore (Italy) between 2001 March–2004 October. The SWIRCAM 256 × 256 HgCdTe detector was employed, yielding a scale of 1.04 arcsec/pix, resulting in a ~4′ × 4′ field of view. Standard techniques of sky subtraction and flatfielding were applied. Four standards were employed for the callibration of the G24.73+0.69 dataset and two for AFGL 2298. All standards were located within the target frames, had *J* band magnitudes between 9.9 and 11.5 mag and were found to be constant to within ±0.02 mag over the course of the observations. The resultant lightcurves are presented in Figs. 1 and 2.

3. Results

Following the apparent minimum reported for AFGL 2298 in 2002 August, we observed the star to brighten by approximately 0.4 mag in the *JHK* bands by 2004 October (Fig. 1). The 2001–4 lightcurve for G24.73+0.69 is presented in Fig. 2 and clearly shows the star to be highly variable. Prior to 2003 G24.73+0.69 exhibited low amplitude (~0.4 mag) variability; which is *suggestive* of a 4–500 day quasi-period. However, in a ~200 day period between 2003 September–2004 April we find an abrupt ~0.7 mag increase in the *J* band, with a subsequent ~0.4 mag increase between April–October. This behaviour is broadly mirrored in both the *H* and *K* bands, yielding an absolute brightening of ~1.1 mag in the year between 2003–4 September in all three bands.

The variability observed for AFGL 2298 was *not* accompanied by any systematic change in $(J-K)$ or $(H-K)$ (mag) colour indices, with median values of 5.65 (range 5.55–5.75) and 2.08 (range 2.04–2.12) respectively. However, significant changes in colour were observed for G24.73+0.69 and we present a colour magnitude plot in Fig. 3, dividing the data into pre- and post-"outburst" subsets. We find a strong correlation between near-IR colours and magnitudes in both subsets, noting that subsequent to the 2003–4 brightening the near IR colours of G24.73+0.69 became significantly bluer. Comparison of the dereddened $(J-K)$ colour index of G24.73+0.69 to the intrinsic colours of supergiants presented by Koornneef (1983) would suggest that prior to 2003 September, the spectal type varied between ~A0 and ~G0. However from spectral analysis we determine a mid-B spectral type at near-IR minimum, while no LBV has been observed with a spectral type as late as G0. Therefore, we infer the presence of an additional contribution to the near-IR flux – either from hot dust and/or the stellar wind – which leads to the conclusion that near-IR photometry alone may not be used to unambiguously determine possible variations in the stellar radius and temperature of LBVs.

This ambiguity is well illustrated by AFGL 2298. Between 2001 June–2002 August spectroscopic data revealed that its temperature increased from 12.5 kK to 15 kK (accompanied by a decrease in radius; Clark et al. 2003a) with little change in IR luminosity or colour due to a corresponding increase in the mass loss rate, which resulted in an increased free-free/free-bound contribution from the stellar wind. We further note that similar behaviour has also been observed for NGC 2363-V1 (P. Crowther 2004, priv. comm.).

However, in the case of G24.73+0.69 we *speculate* that given the similarity in gradients between the 2 branches of the colour magnitude diagram (Fig. 3), the physical process(es) driving the variability were also the same, and the post 2004 April variability is superimposed on a ∼0.7 mag secular brightening of differing cause between 2003 September–2004 April. Moreover, given the significantly bluer near-IR colours post the 2003–2004 brightening we may exclude an increase in mass loss rate and/or an increased contribution from hot dust as possible causes, both of which would lead to redder colours. Thus – by a process of elimination – a variation in the stellar temperature and radius is the most likely cause of the increase in IR luminosity between 2003 September–2004 April.

While the recent changes have been rapid, similarly dramatic behaviour has been observed in known LBVs e.g. M33 Var B (Humphreys et al. 1988). Consequently, given the stellar properties inferred, the presence of a massive circumstellar ejection nebula and now the discovery of significant photometric variability – which we attribute to changes in stellar radius and temperature – we advance G24.73+0.69 as a new Galactic LBV.

4. A revised census of galactic LBVs

In their seminal review, HD94 identify 5 confirmed and 4 LBV candidates in the Galaxy. More recently van Genderen (2001; vG01) increased the number of confirmed galactic LBVs to 8, with 5 ex/dormant and 7 candidates, with Humphreys (2003) subsequently listing a further 3 candidates. In light of the recent growth in IR observations, a new census of galactic LBVs is timely. In compiling this census we adopt the classification criteria of HD94, which in turn were expanded upon by vG01[1].

[1] Despite these criteria explicitly excluding Yellow Hypergiants (YHGs), Smith et al. (2004) recently suggested that the presence of the bistability jump may cause a significant increase in mass loss rate for low mass LBVs, leading to the production of a psuedo photosphere and the appearance of a YHG. Thus we caution that the distinction between low luminosity LBVs and YHGs may be a somewhat artificial distinction between stars in very similar evolutionary states.

The major differences between the classification schemes of HD94 and vG01 were the subdivision of LBVs into strong (s–a; $\Delta \geq 0.5$ mag) and weak (w–a; $\Delta \leq 0.5$ mag) amplitude variables and the inclusion of a new class of ex/dormant LBVs by vG01. While HD94 required a characteristic S Dor or LBV excursion to be of ∼1–2 mag in amplitude, vG01 identified these excursions on the basis of their *optical* colour variability; enabling their identification at much lower amplitudes. Thus, it was possible to identify HD 168607 as a bona fide LBV (e.g. Sterken et al. 1999) despite the low amplitude of the photometric variability observed. vG01 also introduced the ex/dormant classification for those stars which failed to undero either S Dor excursions or eruptions during the 20th century but which showed either other identifying characteristics of LBVs (viz. similar stellar properties and/or the presence of circumstellar ejecta) or had historically shown significant variability prior to the 20th century. However, given the often extremely limited datasets available for many of the new stars presented here, differentiating between ex/dormant and candidate LBVs argueably becomes entirely subjective.

Consequently, in the light of the observational constraints, we choose to modify the scheme of vG01 to simply distinguish between confirmed and candidate LBVs. While we may easily incorporate the members of the ex/dormant subclassification in an expanded candidate LBV census, the appropiate classification for putative weak amplitude variables is somewhat more complex. Specifically, given the absence of a near-IR colour diagnostic it becomes difficult to distinguish between genuine low amplitude LBV or S Dor excursions and variability due to other pulsational modes (e.g. the α Cyg variables) or changes in the contribution from a stellar wind or circumstellar dust.

Nevertheless, of the weak amplitude variables listed by vG01 we may trivially classify both η Carinae and P Cygni as confirmed LBVs. The nature of Cyg OB2 #12 is more debatable. Based on the same observations revealing both spectroscopic and photometric variability ($\Delta \sim 0.5$ mag) Cyg OB2 #12 is variously described as "not [a] fully fledged LBV" (HD94) and "at least an LBV candidate" (Massey et al. 2001), while vG01 classify it as a confirmed weak amplitude LBV. Conservatively, we choose to classify it as a candidate LBV, given that to the best of our knowledge the characteristic temperature/radius variations observed in an S Dor excursion have yet to be observed.

Therefore – upon the adoption of the revised classification scheme of vG01 – we are able to increase the number of confirmed galactic LBVs to 12 and candidates to 23, which we list in Table 1 and discuss below.

4.1. Confirmed LBVs

Including AFGL 2298 and G24.73+0.69, five new LBVs may be identified in the literature. Clark & Negueruela (2004) demonstrate that between 1981–2002 the B supergiant W243 within Westerlund 1 (Wd1) has evolved from an early B to an apparent late B/early A spectral type. Unfortunately, no concurrent photometric lightcurve exists for W243. Nevetheless, assuming a current late B spectral classification for W243 we

Table 1. Summary of the currently confirmed and candidate galactic LBVs. New or reclassified objects *post* vG01 are given in bold type, while the presence of an asterix indicates the star is associated with a gaseous and/or dusty ejection nebula. Note that in the absence of any new data for a given star, we have not attempted to update the relevant classification of vG01.

Confirmed	Candidate
η Car*	Cyg OB2#12
P Cyg*	Pistol Star*
HD 168607	HD 168625*
AG Car*	ζ^1 Sco
HR Car*	HD 326823
HD 160529	HD 316285*
Wra 751*	He 3-519*
FMM 362	HD 80077
AFGL 2298*	AS 314*
G24.73+0.69*	MWC 314*
W243	G25.5+0.2*
GCIRS 34W	G79.29+0.46*
	G26.47+0.02*
	Wra17-96*
	WR102ka*
	LBV 1806-20*
	Sher 25*
	W51 LS1
	GCIRS 16NE
	GCIRS 16C
	GCIRS 16SW
	GCIRS 16NW
	GCIRS 33SE

may infer a change in visual magnitude of ≥0.8 mag – based on the change in bolometric correction implied by the variation in spectral type – confirming its LBV classification.

The K band lightcurve of the Quintuplet member FMM 362 presented by Glass et al. (1999) shows long term variability between 1994–7 with peak to peak amplitude $\Delta K = 0.92 \pm 0.06$ mag, highly suggestive of an S Dor excursion. Recent spectroscopy (Figer 2004) indicates significant temperature variations, confirming the LBV classification of Figer et al. (1999).

The final addition is the Galactic Centre star GCIRS 34W, which Paumard et al. (2001) proposed to be a candidate LBV on the basis of its K band spectral morphology. A near-IR K band lightcurve between 1996–2001 is presented by Ott (2002), which indicates that it was stable with $K \sim 10.8$ mag between 1992 March–1996 June. Subsequently, a ~linear fading was observed, reaching a plateau at $K \sim 11.5$ mag between 1997–1998 and a subsequent minimum at $K \sim 12.1$ mag between 1999–2001. Further observations (T. Paumard 2004, priv. comm.) reveal that this minimum persisted until 2002, from whence GCIRS 34W was observed to have brightened to $K \sim 11.6$ mag.

While the photometric variability is of a magnitude and occurs over a timescale typical for a S Dor excursion, no contemporaneous spectroscopic dataset exists to confirm this interpretation. Nevertheless to generate such variability via changes in the stellar wind would require an extreme mass loss rate at maximum light and would neccessitate substantial changes in the stellar temperature and/or luminosity to drive such changes (e.g. Vink & de Koter 2002); thus we might still infer the presence of an LBV under such an hypothesis.

An alternative explanation might be that the IR emission arises from a highly variable dusty component in the circumstellar environment of GCIRS 34W. To the best of our knowledge only LBVs, supergiant B[e] stars and WCL stars are dust producers amongst the hot massive stars. The spectrum of GCIRS 34W lacks the low excitation features that are common for supergiant B[e] stars; moreover no such star has evidenced such dramatic variability. While dusty WCL stars may undergo large changes in IR flux due to highly variable dust production rates, there is no evidence for the presence of such a star in current spectral data, nor do adaptive optics observations suggest that GCIRS 34W is a composite source such as GCIRS 13E (Maillard et al. 2004), which might host a dusty WCL. Therefore, we conclude that the most likely explanation for the observed variability of GCIRS 34W is a variation in stellar temperature and/or radius, resulting in an LBV classification and noting that alternative explanations for the variability also imply the presence of an LBV.

4.2. Candidate LBVs

Including CygOB2#12, the 5 ex/dormant LBVs and explicitly excluding the YHG IRC +10 420, vG01 lists a total of 12 candidate LBVs, to which we may add a further 11 stars identified via their spectral morphology and, for a subset of 5 stars, the presence of an ejection nebula.

Of the ex/dormant and candidate LBVs, HD 316285 is listed by vG01 as lacking such a nebula; however, as noted by Hillier et al. (1998), the presence of a significant IR excess implies the presence of a dusty component to the circumstellar environment. Recent unpublished data also suggests the presence of a large (~13 pc) bipolar Hα nebula surrounding MWC 314 (A. Marston 2004, priv. comm.). While significantly larger than the typical ejection nebulae seen around LBVs (e.g. Table 9 of Clark et al. 2003b) similar nebulae have been observed around the bona fide LBVs P Cygni (Meaburn et al. 2004) and G24.73+0.69 (Clark et al. 2003b). Despite their extent, an origin in the current LBV phase is suggested by Meaburn et al. (2004); if such a supposition were confirmed it would strengthen the candidacy of MWC 314.

The extreme luminosity and presence of a massive ejection nebula associated with the Pistol Star both point to an LBV classification, while Glass et al. (1999) report variability in the K band lightcurve between 1994–7 with peak to peak amplitude $\Delta K = 0.46 \pm 0.06$ mag. However, as with GCIRS 34W no contemporaneous spectroscopy exists. Moreover, since recent observations of GCIRS 16SW reveal pulsations of a similar amplitude, but over a timescale of ~days (DePoy et al. 2004) – and thus not of LBV origin – we may not discount similar behaviour for the Pistol Star given the rather poor temporal sampling of Glass et al. (1999). Consequently, we consider that the Pistol Star still remains to be confirmed as an LBV.

The candidacy of G79.29+0.46 is suggested by both the observation of spectral variability (Krauss et al. 2000) and the close morphological similarity of both nebula and central star to the confirmed LBVs AFGL 2298 and AG Carina; a resemblance also noted for the newly identified candidates G26.47+0.02 and Wra 17-96. Indeed, given the possibility of photometric variability for G26.47+0.02 (Clark et al. 2003b) we consider all three stars to be strong LBV candidates.

W51 Luminous Source 1 (LS1; Okumura et al. 2000) lies in region of recent star formation in the W51 molecular cloud complex, with an apparent age of 2.3 ± 0.4 Myr. The spectrum presented clearly identifies it as a luminous B supergiant. However, given the presence of low excitation species such as Mg II, Okumura et al. (2000) appear to significantly overestimate both temperature and luminosity (~40 kK and $10^{6.3}$ $L_{\odot}$ respectively). For a more realistic range of temperatures – ~12–20 kK – a luminosity of <10^{6} $L_{\odot}$ is instead suggested. Only one epoch of data is presented, thus no information is available on possible long term variability. Given the confused nature of the Hα image – due to the presence of ongoing star formation – no ejection nebula may be unambiguously identified, although we note the presence of a significant near-IR excess which might signal the presence of hot circumstellar dust.

The six narrow line Galactic Centre stars demonstrate remarkably homogeneous *K* band spectra (e.g. Paumard et al. 2004); given that GCIRS 34W appears to be a bona fide LBV, the remaining five clearly should be considered LBV candidates, as suggested by Paumard et al. (2001, 2004). While Najarro et al. (1997) present an analysis of the spectra of 4 of the 5 stars, we note that the NLTE code employed did not include line blanketing; consequently the stellar parameters reported (~20 kK and >10^{6} $L_{\odot}$) must be regarded as somewhat uncertain (P. Crowther 2004, priv. comm.).

Sher 25 – proposed as a LBV candidate by Smith et al. (2004) – is surrounded by a spectacular bipolar nebula (Brandner 1997), that appears to have been ejected in a blue rather than red supergiant phase (Smartt et al. 2002); consistent with the findings of Lamers et al. (2001) that nebulae around LBVs with $M_{\rm init} \geq 40$ $M_{\odot}$ have also been ejected in the BSG phase. In contrast, the radio nebulae G10.0-0.3 which Gaensler et al. (2001) propose to be causally associated with LBV1806-20, appears unlikely to have originated in a putative LBV phase given its large extent (≥36 pc for the major axis at a distance of ≥12.5 kpc Figer et al. 2004). Despite this, the luminosity of the (binary?) star ($L_{\rm total} \sim 10^{6.3}$ $L_{\odot}$; Figer et al. 2004) and possibility of photometric variability (Eikenberry et al. 2004) support its inclusion as a LBV candidate.

Finally, Homeier et al. (2002) classify WR102ka as a WN10 star, a spectral type that would have previously been classified as Ofpe/WN9. Such stars have previously been suggested as the quiescent "hot" state of LBVs. WR 102ka is found to be positionally coincident with the MSX mid-IR point source G000.0003-00.1743, which has colours consistent with those of a cool dusty ejection nebula (Clark & Porter in prep.). Hence in accordance with the stricture of vG01 not to consider a WNVL star as a LBV candidate without the presence of ejecta, we tentatively advance WR102ka as such.

Table 2. Summary of the transitional stellar population of Westerlund 1; spectral types and designations from Clark et al. (2005) and Negueruela & Clark (2005).

Spec. type	Cluster members
WNVL	44
LBV	243
BIa+	5, 7, 33, 42
sgB[e]	9
YHG	4, 8, 12, 16, 32, 265
RSG	20, 26, 237

We also note in passing the unusual variability that Polcaro & Norci (1998) report for the early type star V439 Cyg. Analysis of long term data reveals apparent photometric and spectroscopic variability, with the star appearing "Mira like" in 1941 and as a Carbon star in 1958, prior to its current appearance as an early B star (Polcaro & Norci 1998, and references therein). However, a recent classification of V439 Cyg as B1Ve by Negueruela (2004) raises the likelihood of missidentification in the past, although an apparent far IR excess attributable to dust emission (Polcaro & Norci 1998) would be atypical for a classical Be star. We therefore reserve judgement on the true nature of V429 Cyg pending future observations.

4.2.1. Transitional stars in Westerlund 1

A census of possible LBV candidates would not be complete without considerations of the stellar population of the massive galactic Super Star Cluster Wd 1. With an age estimated to be ~4 Myr, stars with masses of ~40 $M_{\odot}$ are expected to have just evolved from the Main Sequence, providing a rich potential population of candidates (Clark et al. 2005). While only one bona fide LBV – W243 – has been recognised to date, we list the complete population of transitional objects currently identified in Wd1 in Table 2. Of these, the relation between YHGs and LBVs has already been discussed, while the presence of 3 red supergiants associated with spatially resolved mid-IR and radio nebulae (Clark et al. and Dougherty et al., both in prep.) is of interest given the hypothesis that LBV ejecta may be formed in a (pseudo-)red supergiant phase. Likewise, the presence of a compact radio nebula associated with the sgB[e] star W9 (Clark et al. 1998) raises the possibility of a very recent LBV eruption. Finally, a number of extreme B hypergiants – W5, 7, 33 and 42 – are identified, which show similarities to the LBVs HR Car and HD 168607 (Walborn & Fitzpatrick 2000). While we consider it would be premature to consider this population as LBV candidates at this time, they clearly merit long term monitoring to determine their exact status.

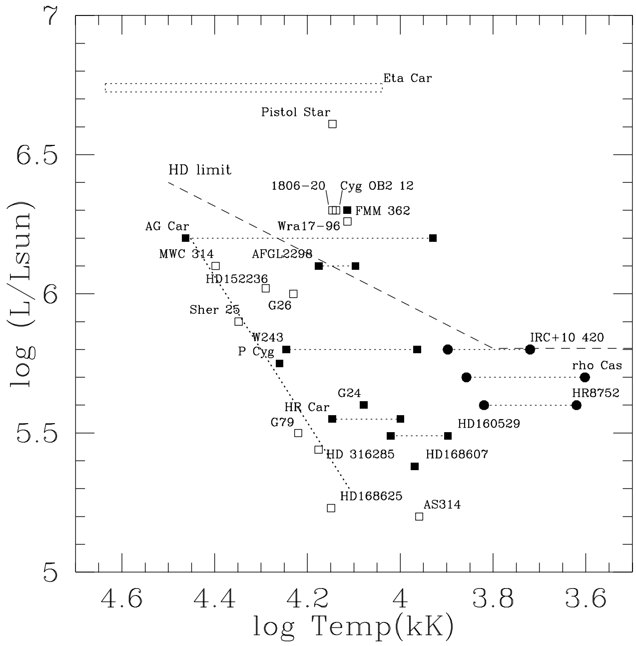

Fig. 4. HR diagram for galactic LBVs (filled squares), candidates (open squares) and YHGs (filled circles). The Humphreys Davidson limit and the best fit to the hot LBV minimum strip (Sect. 5) are also indicated. Luminosity and temperature are from vG01 and Smith et al. (2004) and references therein, except for AFGL 2298 (Clark et al. 2003a), G24.73+0.69 (Clark et al. 2003b), the Pistol Star (Figer et al. 1998), AS 314 (Miroshnichenko et al. 2000), MWC 314 (Miroshnichenko et al. 1998), G26.47+0.02 (Clark et al. 2003b), G79.29+0.46 (Trams et al. 1998), Wra17-96 (Egan et al. 2002), LBV 1806-20 (Figer et al. 2004), Cyg OB2 #12 (Massey & Thompson 1991; Massey et al. 2001) Sher 25 (Smartt et al. 2002) and FMM362 (Geballe et al. 2000; note that the authors regard the current luminosity as a *lower* limit). The location of η Carinae is indicated by the hatched box; the extreme optical depth of the wind preventing a unique determination of the stellar temperature (Hillier et al. 2001).

4.3. Construction of an HR diagram

Unfortunately, the physical parameters of many (candidate) LBVs remain particularly poorly constrained, making the construction of an HR diagram problematic. For the HR diagram presented in Fig. 4 we have adopted the most recent stellar parameters available for each star in question, largely following the references in vG01 and Smith et al. (2004)[2]. However, in addition to the new (candidate) LBVs, several previously identified stars have received revisions; the relevant references are included in the figure caption. Of these we note that there is a significant discrepancy for G79.29+0.46 between the parameters adopted by Smith et al. (from Higgs et al. 1994) and those more recently determined by Trams et al. (1998) which we adopt here[3].

A number of stars listed in Table 1 have intentionally been excluded from Fig. 4; this is due to the large uncertainty in – or complete lack of – estimates of temperature and luminosity. Stars so excluded include the 6 GCIRS stars (see Sect. 4.2), G25.5+0.2, WR102ka, W51 LS1, Wra 751, Hen 3-519 and HD 80077.

Of these the latter three deserve mention. Current temperature determinations for both Wra 751 and Hen 3-519 place them well to the left of the LBV minimum light strip (Sect. 5); however these values appear particularly uncertain. A temperature of 30 kK is typically quoted for Wra 751 (e.g. Hu et al. 1990); however the presence of strong low excitation metallic line emission (Mg II and Fe II) in the *K* band spectra presented by Morris et al. (1996) suggest a substantially lower temperature. Indeed the spectrum is remarkably similar to those of e.g. AFGL 2298, the Pistol Star and G26.47+0.02, which all have temperatures <20 kK. Moreover, upon modeling the nebular properties of Wra 751 Voors et al. (2000) found that a best fit was obtained for a temperature at the low end of the 20–30 kK range investigated.

Turning to Hen 3-519 and modeling by Smith et al. (1994) suggested a tempertature of ~28.5 kK, based predominantly on the strength of the He II 4686 Å transition. However, based on the behaviour of the Balmer lines between 1991–6, Crowther (1996) suggested a substantial downwards revision to only ~20–22 kK. Therefore, given the significant uncertainty in the temperatures of both stars, we have chosen to exclude them from Fig. 4, noting that the significantly lower temperatures suggested would place them within the region of the HR diagram occupied by the remaining galactic (candidate) LBVs.

Finally, the extreme luminosity typically quoted for HD 80077 ($10^{6.3}$ $L_{\odot}$; Carpay et al. 1991) assumes membership of the cluster Pismis 11, and hence a distance of ~3 kpc. However some workers argue for a significantly lower luminosity for HD 80077 – and hence non membership of Pismis 11 – citing as evidence its low mass loss rate and the high transverse velocity, the latter unexpected for a Population I supergiant (R. Humphreys 2004, priv. comm.). Counter to these objections, analysis of ζ^1 Sco reveals a similar luminosity and mass loss rate to that proposed by Carpay et al. (1991) for HD 80077 (P. Crowther 2004, priv. comm.). Moreover, while no corresponding velocities have been determined for bona fide cluster members of Pismis 11, we note that a number of runaway OB stars are also observed with similarly high velocities (e.g. van Rensbergen et al. 1996); however given the proximity of HD 80077 to Pismis 11 a putative ejection event would have occured rather recently. Consequently, while still including it in our list of candidate LBVs, given the significant uncertainty in its luminosity, we exclude it from the HR diagram presented in Fig. 4.

5. Discussion

The dominant feature of the HR diagram presented in Fig. 4 is the clearly delineated high temperature LBV minimum light strip first proposed by Wolf (1989). Unfortunately, the determination of a thickness for this strip and also verification of the low temperature LBV maximum light strip is complicated by the limited datasets available for many stars. Specifically, without long term monitoring encompassing several

[2] Errors in the parameters adopted are discussed at length in Sect. 2.2 of vG01 and Sect. 3 of Smith et al. (2004), who conclude these to be ~0.1–0.2 dex in $\log(L/L_{\odot})$ and 0.05 dex in $\log T$.

[3] Note that the different values merely "slide" the star along, rather than out of, the LBV minimum light strip discussed in Sect. 5.

LBV excursions we risk underestimating the range of temperature variations, leading to a spurious increase in the width of both maximum and minimum light strips. Moreover, our inability to infer a change in temperature from IR photometry alone prevents us from determining the passages of the newly identified LBVs across the HR diagram. This limitation affects AFGL 2298, FMM362, G24.73+0.69 and the Pistol Star, all of which are denoted by a single point in Fig. 4, despite near-IR lightcurves revealing signficant variability.

Consequently, we limit ourselves to revising the position of the well defined *hot edge* of the LBV minimum light strip in Fig. 4. In doing so we explicitly exclude stars such as HD 160529 and HD 168607 from the analysis, given the presence of several (candidate) LBVs of similar luminosity but higher temperature (which in turn suggests a possible width for the hot minimum strip of several kK). Delineated by the minima of the 4 LBVs (AG Car, W243, P Cyg and HR Car) it is characterised by:

$$\log L/L_{\odot} = 2.08 \log T - 3.10.$$

The inclusion of the candidate stars HD 316285, HD 168625, MWC 314, Sher 25 and G79.29+0.46 causes the strip to steepen slightly, the resultant boundary indicated in Fig. 4 and defined by:

$$\log L/L_{\odot} = 2.70 \log T - 5.82.$$

The strip so identified is steeper than that found by vG01, although remarkably similar to that originally proposed by Wolf (1989).

The current dataset does not allow the extention of either the LBV minimum or maximum light strips to $\log(L/L_{\odot}) > 6.2$, despite the presence of 7 (candidate) LBVs with luminosities in excess of this value[4] (including HD 80077 which is omitted from Fig. 4). Given the conclusion of vG01 that LBVs likely spend ~70% of their time close to or in a minimum light hot state, this is perhaps a surprising result. While it might be supposed that the combination of a lack of long term monitoring and a (near-IR) selection effect in favour of mid-B supergiants is to blame, we note that in respect of the later arguement, only FMM 362 and LBV 1806-20 were initially selected *solely* on the basis of their K band spectral morphology.

Assuming the minimum light strip can be extended to higher luminosities, we might expect stars lying on it to have the appearance of highly luminous late WN Wolf Rayets and hence be easily distinguished from the mid B spectral types currently observed (P. Crowther 2004, priv. comm.). However we note that such an extrapolation of the LBV minimum light strip to higher luminosities suggests that it will intersect the Humphreys Davidson limit at $\log(L/L_{\odot}) \sim 6.4$ and ~34 kK (with lower values for both parameters assuming a finite thickness for the strip). Consequently, we might *speculate* that stars with such extreme luminosities that their putative location on an extrapolation of the minimum light strip lies above the HD limit are not able to reside in a stable hot quiescent state and hence that the hot LBV minimum light strip is terminated by the onset of the instabilities implied by the presence of the HD limit. Clearly, concerted photometric and spectroscopic monitoring of such highly luminous objects is required to constrain the LBV phenomenon at extreme luminosities.

Finally, we turn to the circumstellar ejecta associated with the majority of the current census. Based on the properties of the LBV nebulae – and in particular the dust chemistry – various authors have proposed that they are formed in a Red Supergiant (RSG) phase. While it is possible that LBVs with $\log(L/L_{\odot}) < 5.8$ – thus under the low temperature ($T < 6000$ K) HD limit – could have undergone a RSG phase before encountering the instability leading to the LBV phenomenon as they evolved bluewards, the lack of RSGs *above* the HD limit apparently preclude such a passage for LBVs of this luminosity.

Voors et al. (2000) attempt to explain the lack of such highly luminous RSGs by appealing to a combination of both a short lifetime and the rarity of *dusty* LBVs above the HD limit (counting only AG Car for the galaxy). However, the discovery of a large number of new (candidate) LBVs above the HD limit places significant new constraints on this arguement. While a number appear not to be associated with nebulae, we find four new (candidate) LBVs above the HD limit to be associated with *dusty* ejecta (the Pistol Star, Wra 17-96, AFGL2298 & G26.47+0.26). Thus we conclude that any RSG phase – whether evolutionary or as a consequence of the presence of a dense optically thick wind (cf. Lamers et al. 2001) – must be extremely short lived. In this context, the linear dimensions of the nebulae, which suggest ejection histories broadly consistent with AG Car (i.e. implying formation time scales of $>10^3$ yr) present an additional complication for such a scenario[5].

6. Conclusions

We present new observations of AFGL 2298 and G24.73+0.69 that confirm the latter as a new member of the population of galactic LBVs. While we find a correlation between the near-IR magnitude and colour of G24.73+0.69 – as expected for a normal LBV excursion – we conclude that we are unable to unambiguously infer a change in temperature from these observations. With reference to AFGL 2298 and NGC2363-V1, we find that an increase in the mass loss rate of an LBV may lead to the near-IR spectrum becoming redder, despite the underlying star contracting and increasing in temperature. Therefore, determination of the evolution of the stellar parameters of LBVs accessible to IR observations alone requires both photometric *and* spectroscopic observations, in contrast to optically visible stars.

In light of the many recent near-IR observations of highly obscured massive stars we revise the census of galactic (candidate) LBVs presented by vG01, increasing the number of LBVs to 12 and LBV candidates to 23. The significantly increased population permits the construction of an HR diagram

[4] We are implicitly assuming that the extreme luminosities of these stars are *not* due to ongoing non-$M_{\rm bol}$ conserving η Car like erruptions.

[5] In light of the above discussion we caution against inferring a duration for the LBV phase from the age of those nebulae associated with bona fide LBVs, given the possible differences in formation histories for ejecta around high and low luminosity stars.

composed solely of Galactic stars. We are able to confirm the presence of an LBV minimum light strip, extending from $\log(L/L_{\odot}) \sim 5.2$–6.2. Unfortunately, the lack of long term observations prevents us from testing the hypothesis that the strip extends to higher luminosities and also from identifying the corresponding LBV maximum light strip. We note that if extrapolated to higher luminosites, the hot minimum light strip will intersect the HD limit at $\log(L/L_{\odot}) \sim 6.4$; it is therefore not clear that the handful of LBVs that aproach or exceed this luminosity can reside in such a stable hot quiescent state. Finally, the presence of four new (candidate) LBVs associated with dusty nebulae and with $\log(L/L_{\odot}) \geq 5.8$ places additional observational constraints on any theory postulating the formation of the ejecta in (pseudo-)RSG phases for such stars.

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