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Investigating the properties of Galactic Luminous Blue Variables via IR observations

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Abstract: Recent IR surveys of the Galactic plane have revealed a large number of candidate Luminous Blue Variables. In order to verify these classifications we have been undertaking a long term spectroscopic and photometric monitoring campaign supplemented with tailored non-LTE model atmosphere analysis. Here we present a brief overview of selected aspects of this program, highlighting the prospects for identification, classification and quantitative analysis of LBVs in the near-IR spectral window.

1 Introduction

Luminous Blue Variables (LBVs) are massive post-Main Sequence stars that are experiencing a highly unstable phase of evolution that is characterised by dramatic photometric and spectroscopic variability and heavy mass loss. They have been the subject of much recent interest given the twin possibilities that their high mass-loss rates – particularly during transient outbursts – may be essential for the formation of H-depleted Wolf Rayet stars (e.g. Smith & Owocki 2006) and that they may be the immediate precursors of a subset of highly luminous Type II supernovae (e.g. Gal-Yam & Leonard 2009).

Historically, their rarity (e.g. Clark et al. 2005) has meant that their properties – particularly regarding their characteristic outbursts and eruptions (duration, duty cycle, associated mass loss rate and underlying physical cause) – have remained poorly understood. However, recent narrow- and broad-band infra-red surveys of the Galactic Plane have revealed a large number of new LBVs candidates (Clark et al. 2003, Gvaramadze et al. 2010, Mauerhan et al. 2010, Wachter et al. 2010) and it is hoped that studies of an expanded sample size will help elucidate the nature of the LBV phenomenon and its role in massive stellar evolution. However, given their location in the Galactic plane, observations of these stars must be undertaken in the (near)-IR due to significant line of sight extinction. In this contribution we preview the results of a long term spectroscopic and photometric campaign of recently identified candidate LBVs, supplemented with tailored model atmosphere analysis utilising the CMFGEN code (Hillier & Miller 1998); a full description of this program will be presented in Clark et al. (in preparation).

2 Data Reduction and Analysis

Since 2001, near-IR JHK broadband photometric observations of our targets have been obtained with the AZT-24 1.1m telescope in Campo Imperatore (Italy). Contemporaneous spectroscopy has been obtained from a number of facilities including the AZT-24 1.1m, UKIRT, the Mayall 4m and the VLT, while we have also made use of published spectroscopy and photometry. A full description of data collection and reduction will be presented in Clark et al. (in prep.).

Due to the numerous potential sources of near-IR variability – such as continuum emission from the stellar wind, emission/extinction due to circumstellar dust and changes in stellar temperature and bolometric luminosity – it is impossible to constrain the behaviour of LBVs from photometric observations alone. Consequently, where possible, we have undertaken quantitative modeling of the combined datasets; a description of the methodology employed is found in Clark et al. (2009).

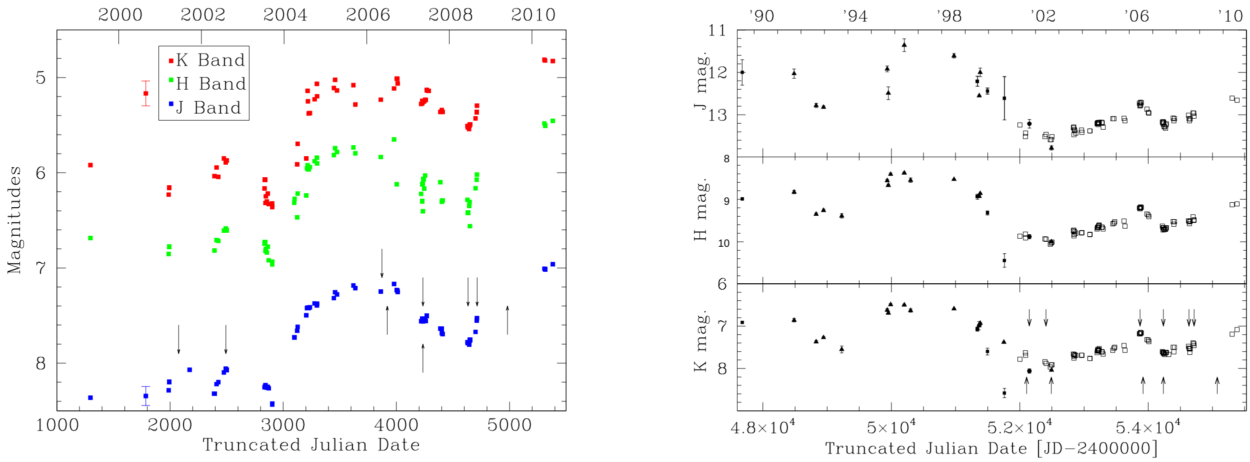

Figure 1: Long term JHK lightcurves of G24.73+0.69 (left panel; Clark et al. in prep) and AFGL 2298 (right panel; Clark et al. 2009). Times of spectral observations are indicated by arrows.

3 Selected Preliminary Results

In Fig. 1 we present sample lightcurves for two recently identified LBVs; AFGL 2298 and G24.73 +0.69 (Clark et al. 2005). Both are clearly variable over $\geq$decades, with $\Delta JHK \geq 1.5$ mag. As such, the timescales and magntitudes of variability are entirely comparable to the results of optical monitoring although, as mentioned above, contemporaneous spectroscopy is required to interpret these data. In the case of AFGL 2298, analysis of such a dataset revealed that its bolometric luminosity varied by more than a factor of two over the course of the observations (Clark et al. 2009). This behaviour was driven by significant changes in the stellar radius, which were accompanied by relatively small changes in temperature (Fig. 2). Recent analysis by Groh et al. (2009) demonstrated that AG Car also varied in bolometric luminosity over the course of its photometric excursions, with a reduction in luminosity as the star expanded and cooled due to the energy required to support the extended outer layers of the star against gravity. However, unlike AG Car, the maximum luminosity of AFGL 2298 occured when its radius was also at a maximum rather than at a minimum; the 'pulsations' of both stars therefore appearing to be of a different character, with those of AFGL 2298 being more reminiscent of a (weak) 'Giant eruption' rather than a canonical 'S Dor' excursion.

A similar dataset also exists for G24.73+0.69 and the results of a comparable quantitative analysis will be presented in a future work, although preliminary comparison of spectra obtained in the transition from photometric minimum (Clark et al. 2003) to maximum (Fig.2) suggests a cooling of the star in a manner analogous to AG Car.

A near-IR spectral classification scheme

Building on this approach, the identification and subsequent spectral follow up of numerous new LBV candidates enables us to define a classification scheme for LBVs in the near-IR as well as investigating the parameter space they occupy and their placement in an evolutionary scheme. We present a montage of K-band spectra of (candidate) LBVs/WN9-11h stars suitable for classification in Fig. 2, along with sample WN8 and Yellow Hypergiants (YHGs) spectra and the results of non-LTE model atmosphere analysis where available.

We highlight the diverse spectral morphology of (c)LBVs, as might be expected given that we sample stars with temperatures ranging from $\sim$8-20kK. Nevertheless, such stars are distinct from the 'normal' Blue Supergiants that also span this temperature range (Clark et al. in prep., Hanson et al. 1996) but which, as a result of their lower wind densities, lack the prominent emission lines of H I, He I and low excitation metals that characterise the spectra of (c)LBVs.

While unfortunately no luminosity dependent features are present in this wavelength range, the presence and line profiles of the various species do allow a gross, qualitative determination of stellar temperature, with the coolest (c)LBVs (T$<$10kK) demonstrating Na I doublet emission and critically lacking He I 2.112μm emission or absorption. At higher temperatures He I 2.112μm is intially observed in absorption, before being driven into emission along with He I 2.058μm and low excitation species such as Mg II and Fe II. At still higher temperatures these lines disappear, leaving a simple emission line spectrum dominated by Brγ and various He I lines. This process also seems to be accompanied by the development of a pronounced P Cygni profile in the He I 2.058μm line. Finally, we note that the He II 2.189μm line appears in emission for the WN8h-9h stars but is absent for the cooler early B supergiants such as P Cygni. It is observed to be weakly in emission in WN9h stars and to show a range of strengths in the WN8 stars due to the large temperature range spanned by this subtype (e.g. WR123 & 124; Crowther & Smith 1996, Crowther et al. 1999), hence it *may* also distinguish between these subtypes (e.g. Crowther et al. 2006). In this respect we note that LHO158, listed as WN8h by Liermann et al. (2009), could formally be classified as WN8-9h.

However, we caution that in the region of parameter space sampled by (c)LBVs and the closely related WN9-11h stars, the K band spectra of such stars can show a degeneracy whereby multiple combinations of stellar temperature, mass-loss rate and H/He ratio may result in similar spectral morphologies (e.g. Hillier et al. 1998). Indeed, this problem may be appreciated by noting the similarities between the spectra of P Cygni and HDE 316285 in Fig. 2 despite the significant difference in temperature between the two stars. We therefore emphasise that tailored, quantitative analysis of the spectra of individual stars over as broad a wavelength range as possible (due to the comparative lack of diagnostics in the K band) is required for the extraction of their physical properties. The Pistol star is a case in point, with Najarro et al. (2009) finding a downwards revision in luminosity by a factor of $>$2.5 over previous estimates following such modeling. Unfortunately, this requires both high S/N and, critically, spectral resolution, given the low terminal wind velocities – v$\leq$500kms^{-1} and typically $\leq$200kms^{-1} – of such stars.

Nevertheless, preliminary results from such analyses show an encouraging continuity in physical properties – and indeed spectral morphologies – with the WN8 stars, with a steady march to higher temperatures and wind velocities at relatively constant mass-loss rates. Such a connection has already been suggested by Langer et al. (1994) and latterly by Martins et al. (2007) based on the evolved population of the Galactic Centre cluster; indeed, analysis of the properties of the (evolved) stellar populations found within young massive clusters is a powerful tool in constraining the passage of

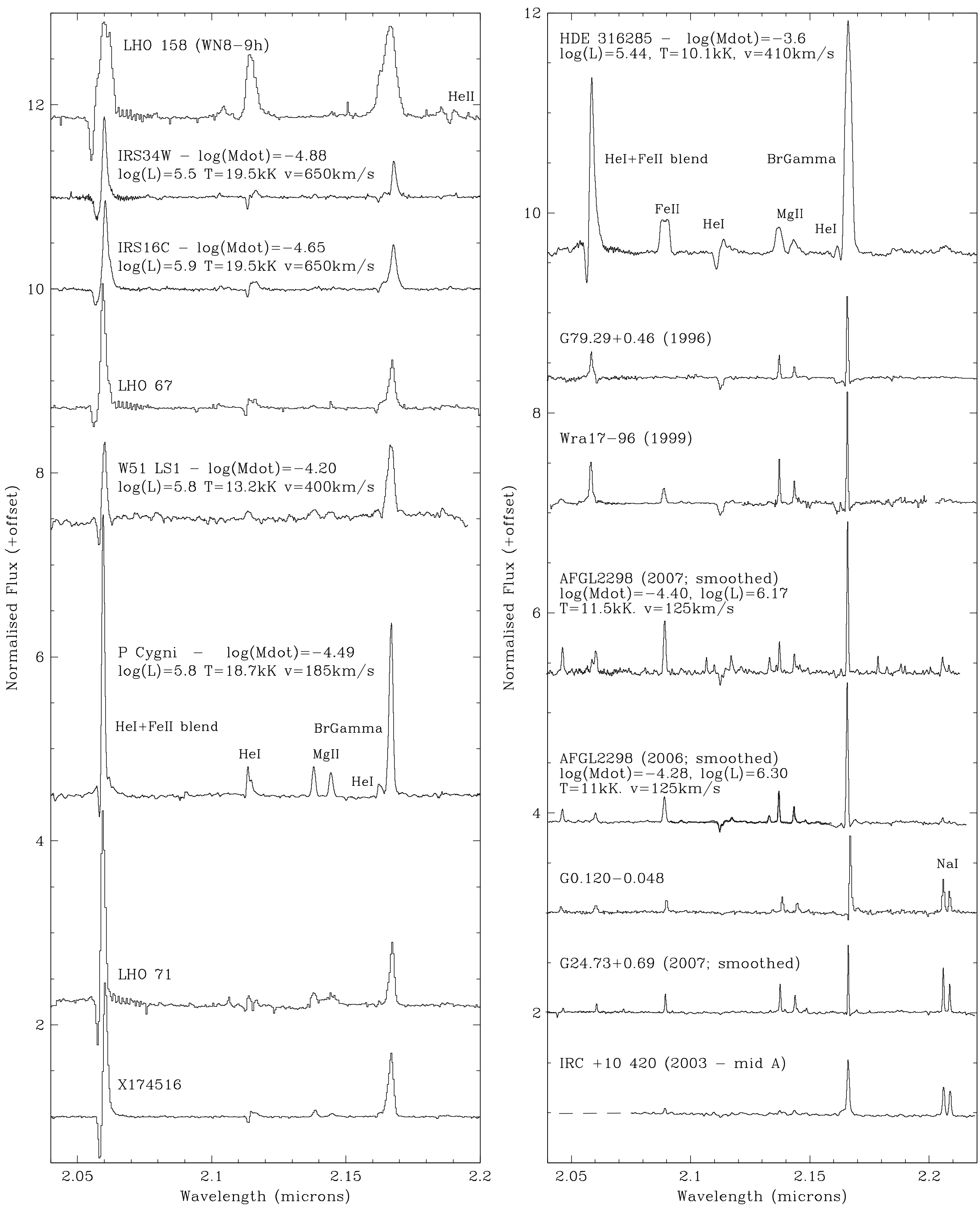

Figure 2: Montage of K band spectra of galactic LBVs demonstrating their diverse morphologies. For comparison the spectra of the Yellow Hypergiant IRC +10 420 and the WN8 Quintuplet member LHO 158 are also presented. For reasons of brevity the references to the origin of spectra and associated analyses have been omitted but are given in Clark et al. (in prep.).

stars from the Main Sequence through the 'transitional' zoo (e.g. Clark et al. 2010). At the other extreme there is a striking similarity between the YHG IRC+10 420 – which is currently evolving to higher temperatures – and LBVs in a cool phase such as G24.73+0.69 and G0.120-0.048. We do not claim that all LBVs evolve directly from YHGs, however; while this might be possible for low luminosity (and mass) stars such as G24.73+0.69, the lack of high luminosity cool super/hyper-giants clearly indicate that stars as luminous as G0.120-0.048 could not have evolved via such a pathway.

4 Concluding remarks and future prospects

While various lines of evidence suggest an important role for LBVs in the late evolutionary stages of massive stars – and by extention their death in SNe and the nature of the post-SNe relativistic remnants – the properties of this phase are still poorly understood, in large part due to the rarity of such stars. However, the recent identification of large numbers of new candidates within the Galactic plane and the viability of studying them via concerted spectroscopic and photometric monitoring supplemented with tailored non-LTE model atmosphere analysis will allow these issues to be directly addressed. Indeed, such work will greatly benefit from near-IR surveys such as VISTA/VVV and the advent of 1-2m class robotic facilities such as the Faulkes Telescopes. Likewise, the availability of multiplexing spectrographs and transient surveys such as PanSTARRS will permit similar studies in external galaxies over a range of metalicities. When combined with radiative transfer modeling of the spatially resolved gaseous & dusty ejecta associated with large numbers of galactic LBVs and which encodes their past mass loss histories, these programs have the potential to advance studies of this transient and violent phase of stellar evolution over the coming years.

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