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Research Note

B 517 – Another very late WNL star in M 33*

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Abstract. We present intermediate dispersion optical spectroscopy of the M 33 star B 517 (Humphreys & Sandage 1980) obtained at the 3.5m Calar Alto and 4.2m William Herschel Telescopes. Our data reveal a spectral type of WN11h, closely resembling the Galactic LBV candidate He 3–519 (Smith et al. 1994). We find that B 517 is the WNL star observed by Esteban et al. (1994), named MC 70 therein, and present a spectral analysis using the Hillier (1990) iterative scheme. We find that its stellar parameters (T_*=27kK, log $L/L_\odot$=5.74, log $\dot{M}/M_\odot$ yr^{-1}=−4.3, v_∞=275 km s^{-1}) are similar to LMC WN11 stars (Crowther & Smith 1996), with a higher helium content (H/He∼0.8 by number), suggesting a post-LBV evolutionary status.

Key words: stars: Wolf-Rayet – galaxies: individual: M 33 – stars: individual: B 517 (M 33) – galaxies: stellar content

1. Introduction

Amongst hot, luminous stars, Ofpe/WN9 stars (Bohannan & Walborn 1989) have recently received considerable interest. Within the past decade, two Ofpe/WN9 stars, R127 (Stahl et al. 1983) and BE294 (Bohannan 1989), have been identified as Luminous Blue Variables (LBVs); during this phase it is believed that extreme mass loss peels off the outer hydrogen-rich atmosphere, to reveal the products of CNO-cycle burning. Recently, Crowther et al. (1995, hereafter Paper I), Smith et al. (1995, hereafter Paper II) and Crowther & Smith (1996, hereafter Paper III) have studied the physical and chemical properties of LMC and M 33 Ofpe/WN9 stars, and identified these objects as either dormant or post-LBVs. From their spectral and chemical properties they revised their spectral classifications to WN9–11. Until recently the only known WN9–11 star in M 33, named MCA1-B, was (accidentally) discovered by Willis et al. (1992), and later analyzed in Paper II. Massey et al. (1996) have subsequently identified five further candidates in M 33 (their UIT008, 045, 104, 236 and 349 sources) based on new optical spectroscopy, and compared these to similar stars in the LMC, confirming our suspicion in Paper II that many such stars are awaiting discovery in external galaxies.

In this research note we discuss the properties of star B 517 from the survey of Humphreys & Sandage (1980). This was found to be a Hα emission source in the survey of Spiller (1992), who proposed a spectral classification of Of/WN9. We find that the WNL star observed by Esteban et al. (1994), located close to the WCE star MC 70 (Massey & Conti 1983) is indeed B 517. Although B 517 was detected in the Massey et al. (1996) survey (their UIT 339), it was not one of the stars for which they obtained spectra, and hence its description given in Sect. 2 is new, revealing a precise WN11h spectral type. We determine the stellar properties of B 517 using the Hillier (1990) atmospheric model in Sect. 3 and discuss its evolutionary status, through a quantitative comparison with its M 33, LMC and Galactic counterparts.

2. Observations

2.1. Identity and photometry for B 517

The Hα-emission source B 517 is located close to the well known ‘Hubble-Sandage’ Variables Var 2 and Var 83 in M 33 (Szeifert et al. 1996). While Humphreys & Sandage (1980) provide an excellent finding chart, reliable coordinates obtained from a POSS plate, relative to astrometric standard stars are α = 01 h 31 m 26.78 s; δ = 30° 21′ 21″.3 (1950), which are in excellent agreement with newly published coordinates of B 517 from Massey et al. (1996). B 517 (and B 518) is visible on the Drissen et al. (1991) Hα image of MC 70. Indeed, comparing the (yellow) finding chart of Humphreys & Sandage (1980) with

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* Based on observations collected at the Calar Alto and William Herschel Telescopes, Spain

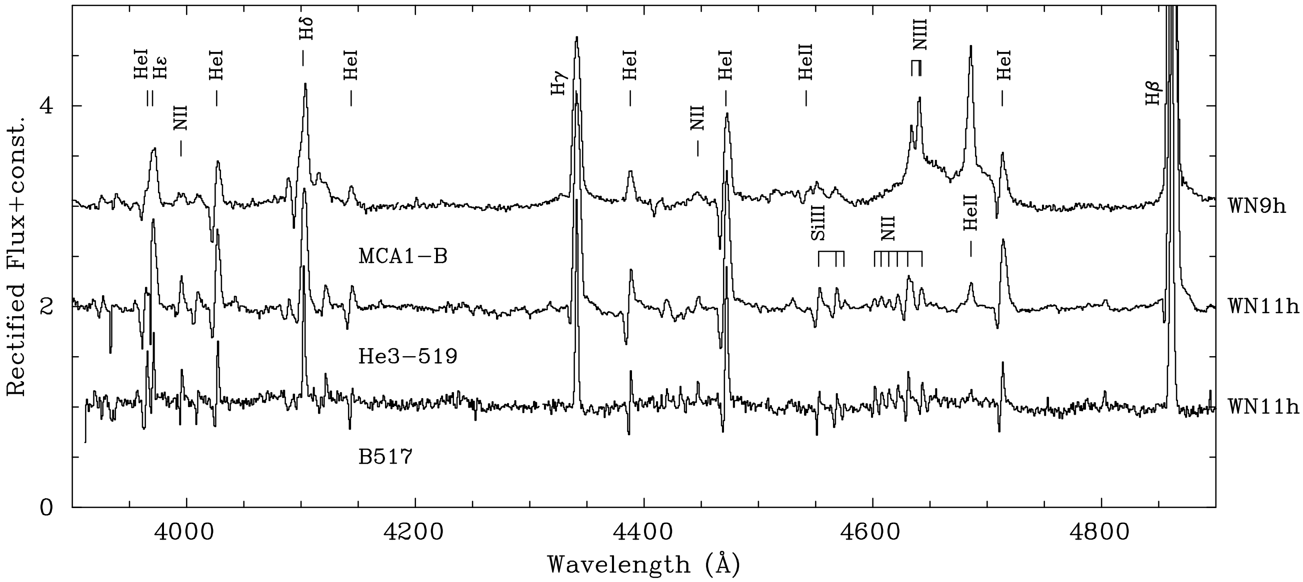

Fig. 1. WHT–ISIS optical spectrum of B 517 (WN11h) covering $\lambda\lambda$3900–4900 and the morphologically related Galactic WN11h star He 3–519 (Smith et al. 1994) with the M 33 WN9h star MCA1-B (Paper II) shown for comparison. Appropriate radial velocity corrections have been applied to the data which are also separated by one continuum unit

Fig. 1k from Drissen et al. (1991) one can see the strong Hα excess radiation of the WNL star.

Photometric measurements for B 517 were obtained in 1989 October at the Calar Alto, with a focal reducer of the Landessternwarte mounted at the 1.23m-telescope and an uncoated GEC CCD detector, and subsequently between 1992 September and 1993 January with the 2.15m-telescope of the Guillermo Haro Observatory at Cananea, Mexico. The LFOSC focal reducer was used in direct imaging mode with a UV-coated EEV CCD detector. Our observations resulted in V=17.93$\pm$0.05 mag and B$-$V=0.05$\pm$0.05 mag. For comparison, previous photographic measurements have been made by Humphreys & Sandage (1980) (V=18.1, B$-$V=0.14) and Ivanov et al. (1993) (V=18.10, B$-$V=0.00, U$-$B=$-$1.20), while CCD photometry has been obtained by Massey et al. (1996, their UIT339) (V=18.03, B$-$V=0.01, U$-$B=$-$0.83). There is therefore no clear evidence for high amplitude variability over the past 20 years. Incidentally, B 517 shows similar ultraviolet and optical colours to the candidate WN9–11 stars newly identified in M 33 by Massey et al. (1996).

Unfortunately, the cross-identification to M 33 WR-star catalogues is difficult. From the recent literature, MC 70 (Massey & Conti 1983) lies 5$''$ north of B 517. Massey & Conti published photometry (V=19.1) and spectroscopy clearly showing broad WC spectral features. Subsequently, objective prism observations of MC 70 were published by Lequeux et al. (1987) (their catalogue number 186) who also detected a (broad) WR emission feature. Ivanov et al. (1993) obtained photographic photometry of B 517 (B 1731 in their catalogue) and suggested a WR origin, from inspection of its close position to MC 70. Esteban et al. (1994) attempted spectroscopic observations of MC 70 and its nebula, however their spectroscopy revealed strong, relatively narrow He I and H I profiles, with weak emission at He II λ4686 on which basis they assigned a WNL spectral type (though they adhered to the MC 70 nomenclature and published coordinates). From comparison with the dataset of Esteban et al. (1994), we can reveal that they actually observed B 517, which is $\geq$1 mag brighter than MC 70 and located 5$''$ to the south. The origin of the ring nebulae in the vicinity of B 517 from Drissen et al. (1991) is unclear; one nebula lies $\sim$7$''$ north east of B 517 (most likely ejected by MC 70) while the second is $\sim$10$''$ to the south.

2.2. Stellar spectroscopy

Our initial spectra of B 517 were obtained at the 3.5m Calar Alto (CA) telescope on 1991 November 17 using the Cassegrain dual beam TWIN spectrograph, and followed up again on 1992 October 6–7. These observations were obtained with 1024$\times$1024 pixel RCA (blue channel) and GEC (red channel) CCDs, 1200 l/mm gratings, yielding partial spectra coverage between $\lambda\lambda$4435–6960 at a resolution (2 pixel) of 1.5–1.8Å. Data were reduced in the same way with the MIDAS software package. After the basic prereduction steps (bias-subtraction and flat-fielding) the spectra were extracted using the method of Horne (1986). Spectra were wavelength-calibrated using He-Ar lamps and normalized by a spline fit through carefully selected continuum windows. A flux-calibration was not achieved due to poor weather conditions.

More recently we have obtained higher quality spectra of B 517 for the purpose of a quantitative analysis using the 4.2m William Herschel Telescope (WHT) with the dual beam Intermediate dispersion Spectroscopic and Imaging System (ISIS) on 1995 October 3. This dataset was obtained using

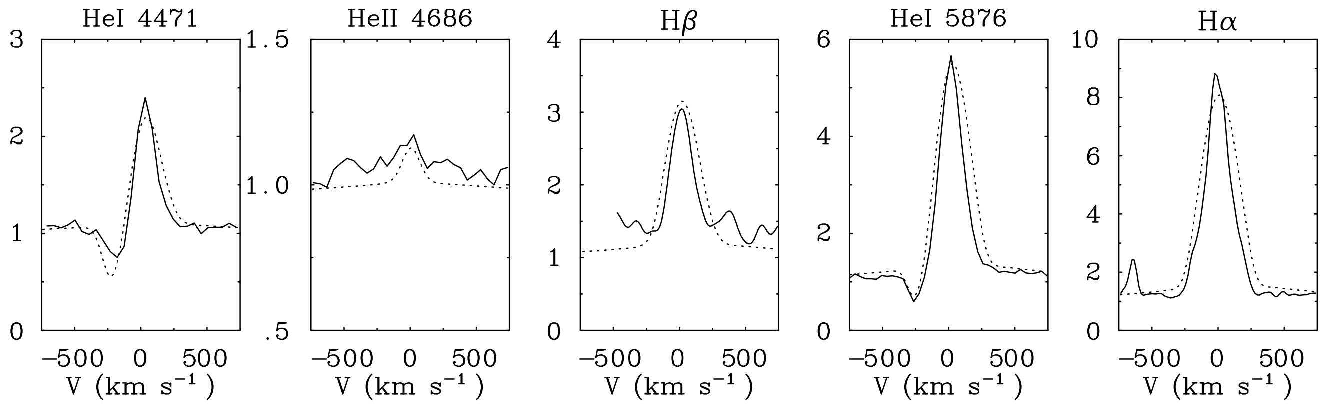

Fig. 2. Comparison of theoretical profiles (dashed) of B 517 with WHT–ISIS observations (solid). Nebular contribution to observed Balmer profiles have been subtracted

Table 1. Derived properties of B 517, and a comparison with related stars in M 33, the LMC and Milky Way (MW) galaxies, including the LBV AG Car at visual minimum. We include wind performance numbers, [($\dot{M}v_\infty$)/(L_*/c)], and Lyman continuum ionising photons, Q_0

Star	Galaxy	WN subtype	T_* kK	R_* $R_\odot$	$T_{\rm eff}$ kK	$R_{2/3}$ $R_\odot$	log L_* $L_\odot$	log $\dot{M}$ $M_\odot$ yr^{-1}	v_∞ km s^{-1}	H/He #	$\dot{M}v_\infty$ / (L_*/c)	(B–V)$_0$ mag	log Q_0 s^{-1}	$M_{\rm V}$ mag	Ref.
B 517	M 33	11	26.5	35	23	1.4	5.74	−4.31	275	0.8	1.2	−0.24	49.1	−7.0	4
MCA1-B	M 33	9	29.4	32	19	2.3	5.84	−4.03	420	2.6	2.8	−0.21	49.2	−7.1	2
S119	LMC	11	27.8	34	26	1.1	5.80	−4.92	230	1.5	0.2	−0.33	49.2	−6.9	3
S142	LMC	11	28.4	28	25	1.2	5.67	−4.80	220	3.0	0.4	−0.30	49.1	−6.6	3
S61	LMC	11	28.3	33	28	1.1	5.76	−4.96	250	1.2	0.2	−0.33	49.2	−6.8	3
He 3–519	MW	11	27.3	31	16	3.1	5.68	−3.90	365	2.0	4.7	−0.15	48.9	−7.1	1
AG Car	MW	11	26.0	52	21	1.6	6.04	−4.25	250	2.4	0.6	−0.27	49.4	−7.7	1

(1) Smith et al. (1994); (2) Paper II; (3) Paper III; (4) this work

1024×1024 pixel Tektronix CCDs (both channels), 600 l/mm gratings at two overlapping settings providing complete spectral coverage between $\lambda\lambda$3910–6885 at a 2 pixel resolution of 1.8Å. Observations were de-biased, divided by a normalized flat-field, and optimally extracted using the PAMELA (Horne 1986) routines within FIGARO (Meyerdierks 1993). The spectra were wavelength and flux-calibrated using the Cu-Ar arc lamps and the Oke (1990) standard star G 191−B2B. Each dataset was then merged, with the final spectrum rectified using low order polynomials, and measured within DIPSO (Howarth et al. 1995). The flux calibrated spectra of B 517 were found to be fairly coincident with existing photometry and spectrophotometry (Esteban et al. 1994), suggesting no significant continuum variability ($\Delta V \leq$0.2 mag) between 1989 October and 1995 October.

2.3. Spectral comparison and classification

In Fig. 1 the WHT–ISIS rectified spectrum of B 517 from $\lambda\lambda$3900–4900 is compared with the M 33 WN9h star MCA1-B (Paper II) and the Galactic WN11h star He 3–519 (Smith et al. 1994), the latter obtained in 1995 April with AAT–UCLES. The spectral appearance of B 517 shows strong similarities with He 3–519, including P Cygni Si III $\lambda\lambda$4552–75 and N II $\lambda\lambda$4601–43 profiles, although narrower profiles overall. B 517 more closely resembles He 3–519 than the LMC WN11 stars (Paper III) which show weaker P Cygni He I profiles and less prominent metal features. It is principally the presence of He II λ4686 emission and non-P Cygni Balmer series which distinguishes B 517 from an emission line B supergiant classification. Other lines observed in B 517 include N II $\lambda\lambda$5667–5730, Si III λ5740 and a very weak C III λ5696 emission, with N III absent. We note that the spectra show no evidence for multiplicity in that the lines are not diluted relative to other related stars and photospheric absorptions from a companion are not detected. From ground based images B 517 appears to be single within a radius of 3″ (Massey et al. 1996), though we emphasise that this does not in itself indicate a single nature for B 517 – recall that at the distance of M 33, 1″ corresponds to a scale of 3.5 pc.

Our spectroscopic observations of B 517 cover 4 years, during which He I line strengths appear to have remained fairly constant (suggesting constant wind velocity and mass-loss rate). Meanwhile, He II λ4686, known to be sensitive to stellar temper-

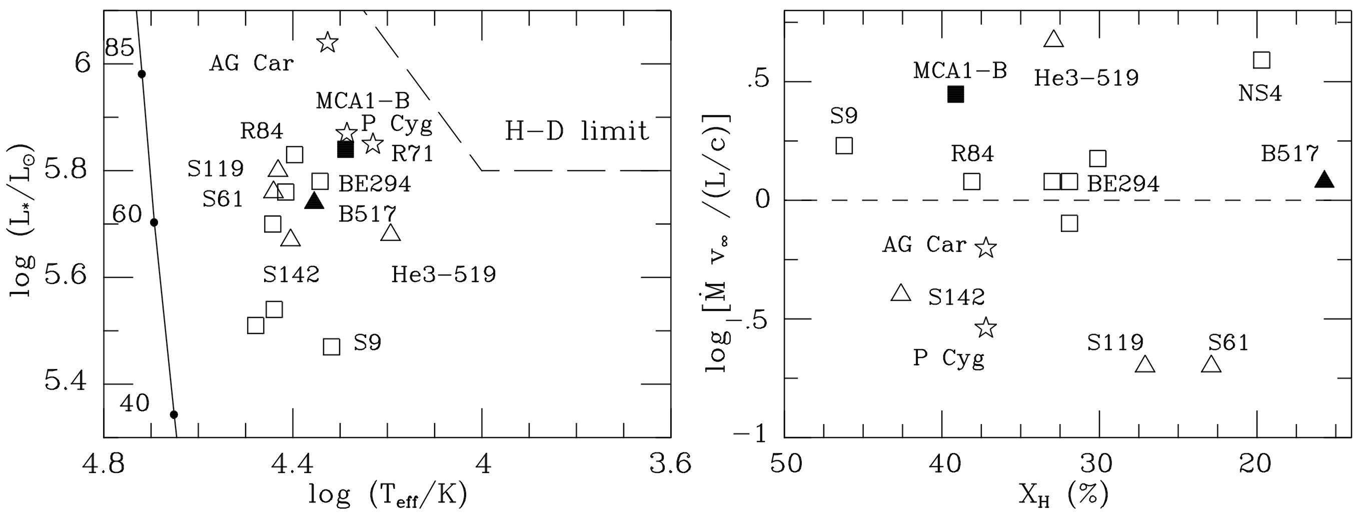

Fig. 3. a Location of WN9–10 (squares), WN11 (triangles) and LBVs (stars) in the LMC and Galaxy (open symbols) and M 33 (filled-in symbols) on the H-R diagram. Data are taken from Papers I–III and Lennon et al. (1994). The zero-age main sequence at Z=0.008 is indicated by a solid line while the dashed line shows the Humphreys-Davidson limit; **b** Derived wind performance numbers for WN9–11 stars (symbols as before) versus surface hydrogen content (by mass), with the single scattering limit indicated (dashed line)

ature changes (Schmutz et al. 1991), appears to have weakened in strength from ≃0.6Å to 0.2Å over this period.

Following Paper III, we obtain a spectral classification of WN11 for B 517 from its observed He I-II line strengths, which are similar to AG Car during its visual minimum phase (Smith et al. 1994). This is consistent with its nitrogen line spectrum, since N II is clearly present, with N III absent (evidence against a Ofpe/WN9 classification). We finally obtain a classification of WN11h due to the presence of strong stellar H I emission (Paper III). Strong [N II] and Balmer nebular features are observed in B 517 (see Esteban et al. 1994) as was previously found for LMC WN11 stars in Paper III.

3. Model results and comparison with other WN9–11 stars

3.1. Spectroscopic analysis

In this section we describe the results of our model analysis of B 517. The model calculations are based on the iterative technique of Hillier (1990) which solves the transfer equation in the co-moving frame subject to statistical and radiative equilibrium, assuming an expanding, spherically-symmetric, homogeneous and static atmosphere. defined by the usual Stefan-Boltzmann relation. We proceed as in Paper III through a determination of stellar parameters via hydrogen (H α) and helium (He I λ5876, He II λ4686) line profile diagnostics together with the absolute flux at V (M_V) and terminal wind velocity, determined from the optical He I P Cygni profiles, and resulting in 275±20 km s^{-1}. For consistency we neglect the possible influence of He II Lyman α photon loss, recently proposed by Schmutz (1996).

Using a standard Galactic reddening law, we estimate an interstellar reddening of E_{B-V}= 0.20[1] towards B 517. Following Paper II, adopting a distance modulus of 24.3 to M 33 from Madore et al. (1985) implies M_V=−7.0±0.3, while a more recent distance modulus estimate for M 33 (e.g. Freedman et al. 1991) would lead to an increase of 0.3 mag in M_V and so correspondingly higher luminosity, radius and mass-loss rate (∼0.1 dex).

We have been kindly provided with the spectroscopic observations of B 517 by Esteban et al. (1994), obtained with WHT–ISIS in 1991 October (i.e. one month prior to our initial observations). This dataset includes higher resolution Hβ and Hα spectroscopy than our own, allowing a more reliable subtraction of nebular contributions, which was achieved using the Gaussian fitting package ELF within DIPSO (see Paper III). Line profile fits from our analysis are compared with observations in Fig. 2. The resulting stellar parameters are T_*=26.5kK, $\log L/L_\odot$=5.74, R_*=35 $R_\odot$, $\log \dot{M}$=−4.3 $M_\odot$ yr^{-1} and H/He∼0.8. Neglecting the nebular contribution to the Balmer series would result in an erroneous stellar hydrogen content of H/He≥3. We obtain a (recession) radial velocity of −220 km s^{-1} for B 517 from stellar and nebular line fits, confirming the results of Esteban et al. (1994).

3.2. Comparison with related objects

Our derived stellar parameters for B 517 are presented in Table 1 and compared to MCA1-B, and all known WN11 stars (prior to

[1] This value is close to the average M 33 reddening of E_{B-V}=0.16 found by Massey et al. (1995), though we cannot exclude values as high as E_{B-V}∼0.30 obtained from the recent UV photometry from Massey et al. (1996) despite the wide-band filters aboard UIT preventing an precise determination

the recent discoveries by Massey et al. 1996). We find that the overall properties of B 517 are fairly typical except for its low hydrogen content. Although quantitative studies of the Massey et al. (1996) WN9–11 sample have not been attempted, their stellar properties are expected to span a similar range to the LMC WN9–11 stars (Paper III), though with lower mass-loss rates as evidenced from their weaker He I profiles (except UIT 008). In our comparison we include the Galactic LBV AG Car since it showed a WN11h spectrum during its recent extreme visual minimum phase (Smith et al. 1994).

In Fig. 3a we show the location of B 517 on the H-R diagram together with known WN9–11 stars and the LBVs R71, P Cyg and AG Car during visual minimum. We estimate present and initial stellar masses of 20 $M_{\odot}$ and 40 $M_{\odot}$ for B 517 from a comparison with the evolutionary tracks of Meynet et al. (1994) for Z=0.008, although the incorporation of additional processes (e.g. rotation) is expected to have a significant effect on evolutionary predictions. From Fig. 3a, B 517 lies near the LBV BE294 and the Humphreys-Davidson luminosity limit (log $L/L_{\odot}\simeq$5.8; the observationally determined upper limit for red supergiants).

In Fig. 3b we present wind performance numbers for WN9–11 stars versus surface hydrogen content, with the single scattering limit shown (dotted-line). B 517 shows the highest surface helium enrichment of any known WN9–11 star with the possible exception of NS4 (WR105, WN9h). Although our sample remains small, the M 33 stars show wind performance numbers between their Galactic and LMC counterparts. B 517 almost lies on the minor axis of M 33, close to the H II-region MA 2 for which Vílchez et al. (1988) found 12+log (O/H)=8.44±0.15, i.e. a metallicity which is also between the solar neighbourhood and the LMC.

From the physical and chemical properties of B 517, it seems highly likely that it shares a common evolutionary history with MCA1-B and the LMC WN9–11 stars, which were concluded as either dormant LBVs or at a phase immediately after this stage (Paper I, III). Due to the high helium content of B 517, we propose that it is most probably at an immediately post-LBV evolutionary phase. This intimate relationship is supported by recent high quality observations of several 'Hubble-Sandage' LBVs by Szeifert et al. (1996), including AF And (M31) and Var 83 (M 33), showing a very similar optical spectral appearance to B 517.

Our observations, incorporating the recent discoveries by Willis et al. (1992) and Massey et al. (1996), indicate a sizeable population of seven WN9–11 stars in M 33, confirming the suspicion from Paper II. It remains crucial to investiate the true population of WNL stars in further regions of massive star formation, through high quality spectroscopy of candidates from recent Hα and UV surveys, allowing detailed quantitative studies to verify their evolutionary and mass-loss properties.

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