Planetary nebulae and their Role in the Universe
ASP Conference Series, Vol. ?, 2002
M. Dopita and S. Kwok, eds.

WR Central Stars

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Abstract. Wolf-Rayet type central stars have been analyzed with adequate model atmospheres. The obtained stellar parameters and chemical abundances allow for a discussion of their evolutionary origin.

1. Introduction

Wolf-Rayet (WR) spectra are characterized by their broad and bright emission lines of He and N (WN) or He, C and O (WC). Although these classes have been established for massive stars, a considerable fraction of central stars (CSPN) show spectra of [WC] type. Their quantitative analysis requires adequate models for expanding atmospheres in non-LTE which are available since one decade (Hillier 1990, Hamann & Wessolowski 1990). Recent versions account for iron-line blanketing and wind clumping (Hillier & Miller 1998, Gräfener et al. 2002).

2. Fundamental stellar parameters

Quantitative spectral analyses of hydrogen-deficient central stars started with late [WC] subtypes (Leuenhagen & Hamann 1994, 1998; Leuenhagen et al. 1996). Early-type [WC]-CSPN have been studied by Koesterke & Hamann (1997a,b). At the high-temperature end, the atmospheric analyses were extended to the "weak emission line stars (wels)", also called [WC]-PG 1159 transition objects, A 30 and A 78 (Werner & Koesterke 1992; Leuenhagen et al. 1993). Central stars of PG 1159 type, showing only thin stellar winds, were analyzed by Koesterke et al. (1998) and Koesterke & Werner (1998). A compilation of these results can be found in Koesterke (2001).

The re-analysis of a couple of stars with line-blanketed models (De Marco & Crowther 1998, 1999; De Marco et al. 2001, Crowther et al., these proceedings) did in most cases not lead to dramatic revisions of the older results. The only *caveat* should be issued with respect to the mass-loss rates. For the analysis of Pop. 1 Wolf-Rayet stars, it became standard to account (in an approximate way) for wind inhomogeneities (cf. Hamann & Koesterke 1998). The density contrast D (which is the inverse of the volume filling factor for the dense clumps, while the interclump space is assumed to be void) has been roughly estimated in a few cases as 4 ... 16. Given the puzzling spectral similarity between massive WC stars and their CSPN counterparts, similar values might apply for the latter as well, although the precise value is hard to determine. The main effect of clumping on the spectral analysis is reducing the empirical mass-loss rates by a factor $\sqrt{D}$. Thus, all mass-loss rates determined without clumping are probably too large by a factor of 2...4.

A major problem arises because important fundamental stellar parameters such as luminosity, radius and mass-loss rate depend on the adopted stellar distance when being derived from a spectral analysis. Unfortunately, there is not a single Galactic [WC]-CSPN with a precisely known distance. The best case is still BD+30°3639 ([WC9]), for which the secular expansion of the nebula has been observed in the optical as well as in the radio range. Together with the expansion velocity from the nebular spectrum, the distance can be estimated. One problem of that method is the identification of line-of-sight and transversal expansion velocities. Harrington (these proceedings) accounts for the non-spherical expansion of the nebula, obtaining a distance of 1.2 kpc. Scaling the previous analyses by Leuenhagen et al. (1996) to that distance, $\log(L/L_\odot) = 4.0$ results while a value of 3.6 is obtained by Crowther et al. (these proceedings). Less accurate are the distances of He 2-113 and CPD -56°8032 determined by De Marco et al. (1997) from interstellar features and the Galactic rotation curve.

The most accurate distance is available for [WC] stars in the Magellanic Clouds. Gräfener et al. (these proceedings) carefully analyzed HST spectra of the [WC4] star LMC-SMP 61 (cf. Fig. 1) by means of line-blanketed model atmospheres, obtaining $\log(L/L_\odot) = 3.9$ for the luminosity. The few [WC]-CSPN with known distances are plotted in an HR diagram in Fig. 2. As the comparison with any set of evolutionary post-AGB tracks reveals, their luminosities correspond to a stellar (core) mass of about $0.6\,M_\odot$. This just matches the sharp maximum in the mass distribution of White Dwarfs and proofs that hydrogen-deficient central stars are not distinguished from hydrogen-rich CSPN by a particularly high (or low) mass.

A special case is the enigmatic central star N66 in the LMC, the only [WN]-type central star known so far (the detection of a Galactic [WN] star is reported by Parker, these proceedings). N66 has undergone a dramatic brightness change on the time scale of years. A preliminary analysis of the whole time-series of observations (cf. Peña et al., these proceedings) yields a luminosity of $\log(L/L_\odot) \approx 4.5$ before and after its outburst, which would correspond to a very high core mass if this object is a post-AGB star at all. At its brightness maximum in 1994 a luminosity of about $10^{5.4}\,L_\odot$ was reached for a short time.

3. Chemical abundances: empirical data

The chemical composition in the expanding atmospheres of hydrogen-deficient central stars have been determined by the spectral analyses performed with the Kiel-Potsdam code (same references as in the first paragraph of the preceding section). The CNO abundances obtained by those studies are graphically represented in Fig. 3 (full symbols). In all cases, an oxygen abundance of the order of 10% has been found. The helium-to-carbon mass ratio He:C is about 1:1 for [WCL], wels and PG 1159 stars (with large scatter in the latter class). However, for [WCE] subtypes a He:C ratio of about 2:1 has been determined, which would contradict the idea of a unique evolutionary sequence.

All wind analyses quoted so far have employed models which not yet accounted for iron-line blanketing. Therefore the analyses should be repeated with

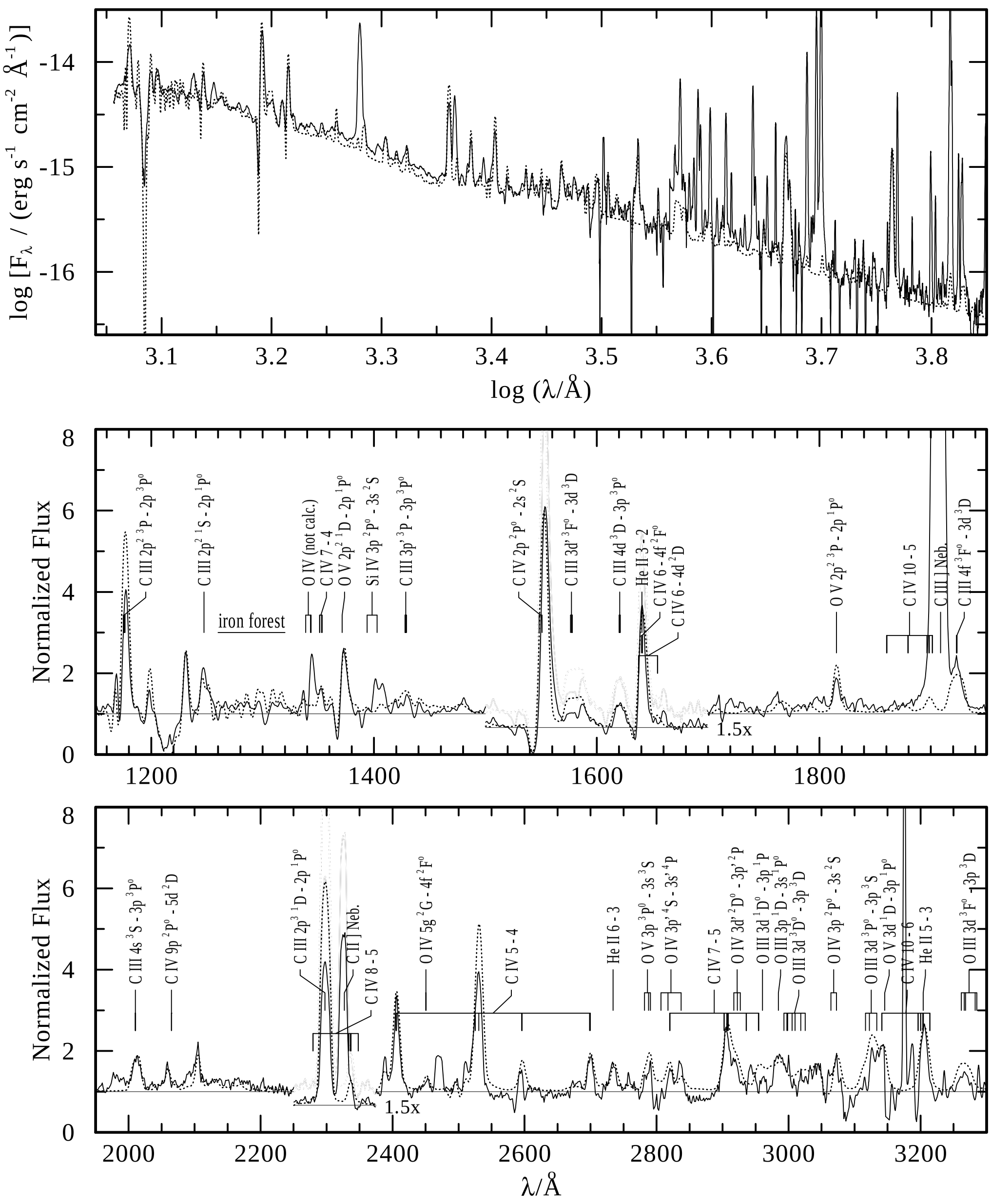

Figure 1. Spectral fit for the [WC4] Central star SMP 61 in the LMC. The HST observations (solid lines) are compared to a model (dotted lines) with $\log L/L_{\odot} = 3.9$, $T_{*} = 88\,\mathrm{kK}$, and $v_{\infty} = 1400\,\mathrm{km/s}$. The abundances are He:C:O = 45:52:03 (by mass), and 1/4 solar for Fe. The mass-loss rate is $\log[\dot{M}/(M_{\odot}\mathrm{yr}^{-1})]$ = -6.17 (clumping contrast D = 4). A theoretical nebular *continuum* has been subtracted from the dereddened ($E_{B-V} = 0.12\,\mathrm{mag}$) observation, before it is compared to the model flux in the upper panel. The other two boxes display the UV part in more detail, after the spectra were divided by the theoretical stellar continuum for normalization.

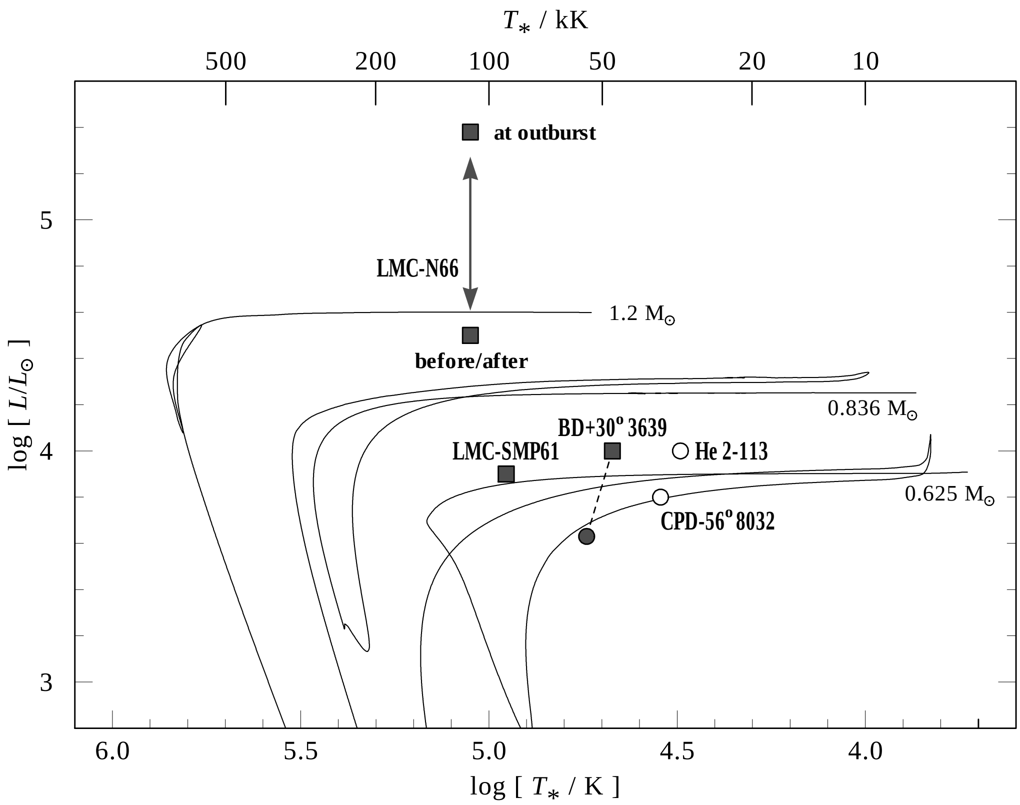

Figure 2. Hertzsprung-Russell diagram with hydrogen-deficient central stars of well-determined luminosities based on known distances (full symbols): N66 and SMP 61 ($d = 50$ kpc from LMC membership), BD +30°3639 ($d = 1.2$ kpc from the secular expansion of the nebula). The results by Leuenhagen et al. (1996) and Crowther et al. (these proceedings) are represented by a square and a dot, respectively. The distances of He 2-113 and CPD -56°8032 (open symbols) are from less reliable methods (see text). Evolutionary tracks (from Blöcker 1993, 1995; Paczyński 1970) are shown for rough comparison and reveal that all four [WC] type central stars have most likely masses around 0.6 $M_\odot$. Only the outbursting [WN] star N66 is much more luminous.

the line-blanketed model atmospheres available now. This has been done for four [WCL] stars by De Marco & Crowther (1998, 1999) and De Marco et al. (2001) (the latter study giving two alternative sets of abundances for SwSt 1). Four more stars, including two [WCE] stars, have been added recently (Crowther et al., these proceedings). The results are represented in Fig. 3 by *open* symbols (NGC 40 results being identical with the previous ones). The recent analysis of LMC-SMP 61 (Gräfener et al., these proceedings) have also been obtained with line-blanketed models and are therefore represented by open symbols as well. These results seem to indicate that the He:C ratio has been overestimated in the older [WCE] analyses. We expect that the average He:C ratios will finally

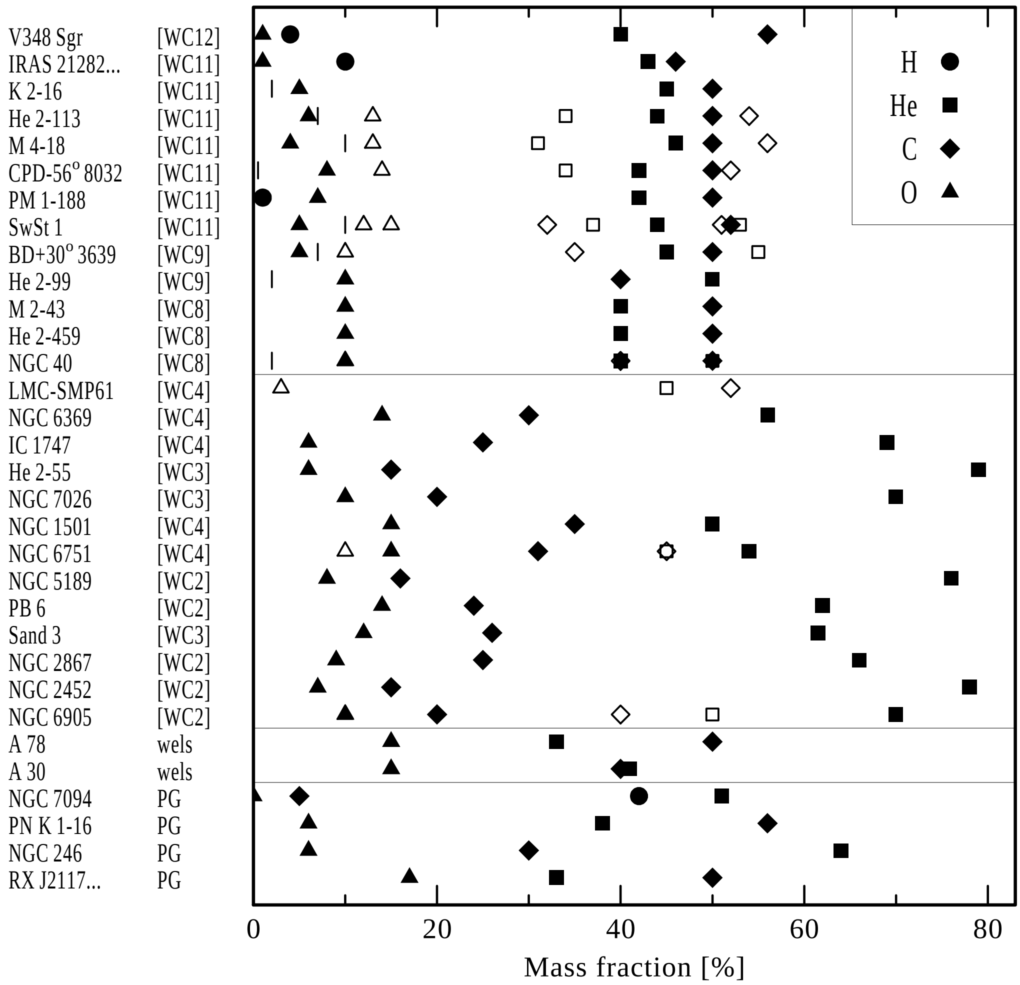

Figure 3. Atmospheric abundances in hydrogen-deficient central stars obtained from spectral analyses (see text for references). Filled symbols are based on studies with un-blanketed model atmospheres, while open symbols represent values obtained more recently with line-blanketed models. Oxygen contributes roughly 10% (by mass) the atmospheres. The He:C ratios seems to be different between the different classes, but are also due to large revisions when stars were re-analyzed with blanketed models. Hydrogen has been detected in few stars of latest [WC] subtype. Small vertical bars indicate upper limits of the hydrogen abundance.

arrive at about 1:1 when more [WCE] stars have been re-analyzed with the upgraded models.

On the other hand, most of the re-analyses of [WCL] stars now yielded He:C ratios smaller than unity, once more disturbing the harmonic picture of a common evolutionary connection between all classes of hydrogen-deficient central stars. More careful analyses are needed to reveal if there are really systematic differences between the composition of [WCL], [WCE] and PG 1159 stars.

The detection of hydrogen in [WC]-type central stars has been a surprise. The clearest hydrogen signature is found in the spectrum of the latest subtype, V 348 Sgr [WC12], where an H abundance of 4% was determined by Hamann & Leuenhagen (1994). Similarly, small abundances of H were found in the [WC11] stars IRAS 21282+5050 and PM 1-188. Upper limits established for a couple of other [WCL] stars do not exclude traces of hydrogen.

No hydrogen has been found yet in early [WC] subtypes. However, in hotter stars the stellar He II and nebular Balmer blends, together with the higher wind velocity, inhibit sharp detection limits. That hydrogen is found only in the latest subtypes might thus be a selection effect.

While the detection of hydrogen in PG 1159 stars is also difficult, some of them (called "hybrid" PG 1159 type) display a surprisingly high hydrogen abundance (e.g. NGC 7094). As a further fact about post-AGB stars, one should keep in mind that a considerable fraction of White Dwarfs is hydrogen-free (i.e. not of DA type). In contrast to [WCL] or PG 1159 stars, the hydrogen detection limit is extremely sharp here, because – as long as the atmosphere is quiet – gravitational settling would make any hydrogen floating at the surface.

Iron abundances have been determined only recently for a few hydrogen-deficient central stars from the "iron line forest" in the UV, and were generally found to be very small. Gräfener et al. (these proceedings) showed that in LMC-SMP 61 iron is below 1/15 solar, Crowther et al. (these proceedings) restricted the Fe abundance to 0.2...0.5 times the solar value for the two galactic [WC]-CSPN BD+30°3639 and NGC 40, and Werner et al. (these proceedings) found underabundances in PG 1159-type stars. — Determinations of further trace elements only exist for a few [WC] stars of latest subtypes (Leuenhagen & Hamann 1998). In earlier subtypes the higher wind velocities cause broader spectral lines, making weak features from rare elements undetectable.

4. Chemical abundances: evolutionary origin

The observed chemical composition of Wolf-Rayet-type central stars provide important constraints for discussing their evolutionary origin. "Classical" models of (post-) AGB stars failed in producing the basic mixture – about equal amounts of helium and carbon with several percent of oxygen – in *any* of their interior layers. Only since the effect of diffusive mixing in overshoot layers is taken into account (Herwig et al. 1997), the models produce appropriate mixtures in the "intershell region" between the hydrogen- and helium-burning zone. The remaining problem is how to display this material at the stellar surface. This can be achieved by a last "thermal pulse". The resulting surface composition depends on whether this last pulse occurs already at the tip of the AGB (Asymptotic giant branch Final Thermal Pulse, AFTP), during the horizontal post-AGB evolution through the CPN region (Late Thermal Pulse, LTP), or even later after hydrogen burning already ceased and the star entered the cooling track (Very Late Thermal Pulse, AFTP). For particular evolutionary sequences, Herwig (2001) obtained the following abundances for stars undergoing the different scenarios:

- AFTP: H:He:C:O = 17:33:32:15 ... 55:31:07:04 (depending on details)
- LTP : H:He:C:O = 02:37:40:18
- VLTP: H:He:C:O = 00:38:36:22

Thus, all of these models predict about equal amounts of He and C, as in the empirical data, while oxygen is somewhat higher than observed.

Most striking is the difference in the predicted hydrogen abundance. When the hydrogen envelope mixed with deeper layers, it is more or less diluted in the AFTP and LTP case but completely burnt in the VLTP. It is tempting to assume that those post-AGB stars which are completely free of hydrogen (i.e. an unknown fraction of all [WC]-CSPN, and the non-DA White Dwarfs) originate from the VLTP, while those objects with a (hitherto detected or still undetected) small rest of hydrogen came via the AFTP or LTP channel. However, there are inconsistencies in this picture, concerning the branching ratio. Given the considerable number of non-DA white Dwarfs, there should be many stars suffering the VLTP. In contrast, the PN around [WC] stars are on the average not older than other PN (Górny & Stasińska 1995), favoring their direct descendence from the AFTP.

Another achievement of recent evolutionary calculations is the accounting of "simultaneous mixing and burning" (Herwig 2001). The models predict that neutrons are produced via C^{13} in the intershell region, which then produce s-process elements. Unfortunately, the spectra of [WC]-CSPN are not suitable to reveal detectable lines of such trace elements. However, the recent determination of iron *under*abundances in hydrogen-deficient post-AGB stars gives indirect evidence that s-process nucleosynthesis has been effective in those stars, because Fe is consumed by the neutron capture when being transformed into heavier elements.

5. The mass-loss mechanism

Massive (Pop. 1) Wolf-Rayet stars and WR-type central stars share the same enigma. In both cases there are hydrogen-rich and hydrogen-deficient stars at the same location in the HR diagram, and in both cases the hydrogen-deficient stars develop much higher mass-loss (by a factor of 10 ... 100) than their hydrogen-deficient counterparts. While the thinner winds of the hydrogen rich stars (Pop. 1 as well as CSPN) can be explained by the radiation-driven wind theory, consistent models are not yet available for Wolf-Rayet type winds. In any case, such theory must explain while the hydrogen-deficient stars have much stronger wind than stars of same luminosity, radius and effective temperature but normal composition. Three possible hypotheses run into contradictions very quickly:

- The higher mass-loss from hydrogen-deficient stars is a (non-linear) response to their lower stellar mass. – This is certainly true for Pop. 1 stars because of the different mass-luminosity relation for O and WR stars, respectively. However, central stars should all follow the same (core) mass-luminosity relation, and we found no differences between the typical luminosity of [WC]-type and other central stars (Sect. 2).

- The stronger winds from hydrogen-deficient stars are directly due to the atmospheric composition, as the heavy elements intercept more radiation pressure. – This might hold for WC stars because of their CO enrichment. However, this explanation fails for the (Pop. 1) WN stars, as their content of heavy elements is not enhanced, only hydrogen is converted into helium which are both almost inert for radiation pressure.

- Due to their inner structure, WR stars are violently unstable against (non-radial) pulsations which initiate the mass-loss at the base of the wind. – Corresponding instabilities against pulsations are indeed predicted theoretically for massive WR stars. Central stars, however, have a completely different structure, and it is very unlikely that pulsations play exactly the same role in both cases, and anyhow they are not observed in general.

Summarizing, we state that there is an increasing amount of empirical data on WR-type central stars obtained from spectral analyses. Their evolutionary origin is not yet clear in detail, but so far the basic idea is a last thermal pulse which destroys the hydrogen envelope, followed by a sequence [WCL] → [WCE] → [WC]-PG 1159 → PG 1159 → WD.

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