Mass-loss rates and C/He ratios in the winds of the WC central stars of planetary nebulae

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ABSTRACT

We estimate the C/He ratio in the central star winds of five planetary nebulae that have WC spectra: SwSt-1, He2-99, He2-113, BD + 30°3639 and NGC 5315. These estimates take into account optical depth effects in the wind. Our results indicate that 0.41 < C/He < 0.68 by number, suggesting exposure of He-burned material. If helium and carbon are the dominant elements in the winds of those stars, the mass-loss rates are in the range 5.7 × 10⁻⁷ to 6.7 × 10⁻⁶ M☉ yr⁻¹, substantially higher than previous estimates.

Key words: stars: abundances – stars: mass-loss – planetary nebulae: general.

1 INTRODUCTION

Planetary nebulae (PN) are the end products of intermediate-mass stars. The shell ejection probably occurs at the end of the asymptotic giant branch (AGB) evolution. AGB stars in a double shell burning phase lose mass through a ‘fast wind’ until the mass of the H-rich envelope is reduced below a critical value. The transition to the PN region may occur in several different situations (Schönberner 1989): (i) during quiescent H-burning at constant luminosity; (ii) after a thermal pulse of the He shell; or (iii) during quiescent He-burning. These different paths may be the key to understanding H-deficient and C-rich central stars of planetary nebulae (CSPN). DA white dwarfs probably originate from CSPN leaving the AGB with an H-rich photosphere (Mendez 1991). On the other hand, H-deficient CSPN probably result from ejection during a thermal pulse or during He-burning, when He-burned material is exposed at the remnant surface.

UV spectra of CSPN indicate that most of those objects are losing mass. In particular, Cerruti-Sola & Perinotto (1985) concluded that all CSPN in their sample with WR spectra have a detected wind in the UV, and estimated mass-loss rates in the range 10⁻¹⁰−10⁻⁷ M☉ yr⁻¹ for the stars studied. Hutsemekers & Surdej (1989) reanalysed that sample, concluding that the mass-loss rates are well above the expected values derived from a simple extrapolation of the mass-loss versus luminosity relation verified for OB stars.

Mass-loss estimates from UV lines require, in general, knowledge of the average ionization fraction of the ion under consideration throughout the expanding envelope, and its relative abundance. Useful UV lines for mass-loss diagnosis are, for example, O IV λ1341 and O V λ1371. A common assumption used in most of the analyses found in the literature is that those ions are the dominant species and, therefore, that X(O IV) + X(O V) = 1 (where X is the ionization fraction). An additional assumption concerns the chemical composition of the wind, which is usually assumed to be the same as that of the associated nebula. In fact, many CSPN are extremely hydrogen-deficient. De Freitas Pacheco & Veliz (1987), in their analysis of the central star of SwSt-1 (type WC10), raised the possibility that the wind from this object does not have the same chemical composition as the associated nebula. More recently, Kaler et al. (1989) analysed in detail the UV and optical spectra of He2-99, also a WC-type central star. They concluded that the carbon-to-helium ratio in the wind is about 0.3, similar to the values found in Population I Wolf–Rayet (WR) stars (de Freitas Pacheco & Machado 1988). Thus, at least in CSPN with a WC spectrum, the wind has a chemical composition distinct from that observed in the outer nebula. These H-deficient CSPN may result from the removal of an H-rich envelope as a consequence of a late He-shell flash. The star returns to the AGB with an additional severe mass-loss phase (Iben 1984, 1989), exposing nuclear matter processed through He-burning.

In the present work, as a contribution to the study of the evolutionary status of CSPN with WC spectra, we report a spectroscopic analysis of five objects. We estimate the C/He ratios in the winds of these stars and also the mass-loss rates. Our study indicates that the C/He ratio is in the range 0.41 < C/He < 0.68, suggesting exposure of He-burned material. Moreover, if helium and carbon are the dominant elements in the winds of those stars, the mass-loss rates are in
the range $5.7 \times 10^{-7}$ to $6.7 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$, substantially higher than previous estimates.

2 OBSERVATIONS

Spectra of the programme stars were obtained using the facilities of the National Laboratory for Astrophysics (Brazopolis, Brazil). Cassegrain observations, using an intensified Reticon as detector and with reciprocal dispersion of about 1.1 Å pixel$^{-1}$, were performed on 1988 July 22–24. Coudé spectra, using a CCD as detector and with a reciprocal dispersion of about 0.5 Å pixel$^{-1}$, were obtained during runs on 1989 March 24–25 and 1990 May 28–31.

The data were reduced using a standard procedure on the VAX 8530 of the University of São Paulo. Figs 1(a) to (e) show coudé observations of selected spectral regions of our programme stars. Table 1 gives the equivalent widths of the main lines produced in the wind that were used in our analysis.

BD+30°3639 was observed by Smith & Aller (1971). We have compared our measured equivalent widths with theirs. The agreement is good and no systematic differences were found. On average, the differences amount to about 18 per cent. This is consistent with our estimated errors, which are about 20 per cent. The same remarks apply to the comparison with the He2-99 data of Kaler et al. (1989).

3 THE METHOD OF ANALYSIS

Inspection of Fig. 1 reveals that many lines display a P Cygni profile, indicating optical effects in the wind. Many of the transitions cannot, therefore, be considered optically thin throughout the expanding envelope. In this case, if $l$ and $u$ label the upper and the lower levels of a given transition, the luminosity due to such an emission line is

$$L_{ul} = \int n_u^2 A_{ul} h v_{ul} \beta_{ul} (1 - W_s) 4\pi r^2 \, dr,$$

where $n_u^2$ is the number density of a given ion for the energy level $u$, $A_{ul}$ is the transition probability per unit time of the considered transition, $\beta_{ul}$ is the local escape probability of a photon of energy $h v_{ul}$, and the factor $(1 - W_s)$ takes into account the screening of the star ($W_s$ is equal to the geometrical dilution factor in a first approximation).

We assume that the velocity profile in the envelope is given by

$$V^2(r) = V_0^2 + V_\infty^2 \left(1 - \frac{R}{r}\right),$$

where $R$ is the photospheric radius of the star. In the presence of a significant velocity gradient, the Sobolev approximation (Sobolev 1957; Castor 1970) can be used to calculate the local escape probability, i.e.,

$$\beta_{ul} = \frac{(1 - e^{-\tau_{ul}})}{\tau_{ul}} \frac{d\Omega}{4\pi},$$

where

$$\tau_{ul} = \sigma_{ul} \lambda_{ul} n_l [1 - (n_u g_l / n_u g_u)] / [d V / dz],$$

and we have introduced

$$\sigma_{ul} = \frac{\pi e^2}{m c} f_{ul}. \tag{5}$$

In the above formulae, $f_{ul}$ and $\lambda_{ul}$ are respectively the oscillator strength and the wavelength of the transition, $g_i$ is the statistical weight of level $i$, $d V / dz$ is the velocity gradient in the line of sight and the other symbols have their usual meanings.

Let the population density of a given level $j$ of an ion in a state of ionization $s$ be given by

$$n_j^s = b_j g_j F(T_e) \exp \left( \frac{E_j}{kT_e} \right) n_e n^{s+1}, \tag{6}$$

where $b_j$ is the departure coefficient from local thermodynamic equilibrium (LTE), to be calculated from the statistical equilibrium equations (see Appendix), $E_j$ is the energy of level $j$ with respect to the continuum, $n_e$ and $T_e$ are respectively the electron density and the temperature, and $n^{s+1}$ is the number density of the element under consideration in the ionization state $s + 1$.

Let us now define the average ionization fraction of a given ion $Y^n$ throughout the envelope by the relation

$$\langle X(Y^n) \rangle = \frac{\int n_n n(Y^n) \, dV}{\int n_n n(Y) \, dV},$$

where $n(Y) = \sum n(Y^n)$ is the total number density of the element Y (helium or carbon in our case). In this case, the electron density is approximately given by

$$n_e = \left( \sum_{m=0}^{2} m(X(He^m)) + A \sum_{m=0}^{5} m(X(C^m)) \right) n(He) = \xi n(He), \tag{7}$$

where $A = n(C)/n(He)$ is the carbon abundance relative to helium. From the continuity equation, the helium density can be written as

$$n(He) = \frac{M}{4\pi V^2(1 + 3A) \rho_{He} V(r)}. \tag{8}$$

Under these conditions, introducing the dimensionless variables $w = V(r)/V_\infty$ and $x = r/R$, and defining $\mu = \cos \theta$, after some algebra we can write, for the Sobolev effective optical depth,

$$\tau_{ul} = \tau_{ul}^w F(\mu, w, x),$$

where the parameter $\tau_{ul}^w$ depends on various model and stellar parameters:

$$\tau_{ul}^w \propto \xi (X(Y^{n+1})) \delta(A) \frac{M^2}{R^3 V_\infty^3},$$

and where $\delta(A) = 1/(1 + 3A)^2$ for He ions and $A/(1 + 3A)^2$ for C ions.

In equation (10), the function $F(\mu, w, x)$ is defined as

$$F(\mu, w, x) = \frac{1}{(xw)^3[1 + \mu^2[(d \ln w / d \ln x) - 1]]}. \tag{11}$$
Figure 1. Coudé observations of selected spectral areas of the programme stars, with the transitions used in our analysis.
parameter \( \tau_{\text{obs}}^i \). From the observed line equivalent width we derive the corresponding \( \tau_{\text{obs}}^i \) for that ion.

(iii) From equation (11) it is easy to verify that the ratio of the sum of the \( \tau_{\text{obs}}^i \)'s for the carbon and helium ions is \( A = \text{C}/\text{He} \).

(iv) The mass-loss rate can also be derived from equation (11) once the relative abundance \( \text{C}/\text{He} \) has been estimated.

4 RESULTS

The adopted stellar parameters are given in Table 2.

For SwSt-1, the effective stellar temperature and distance have been taken from de Freitas Pacheco & Veliz (1987). For the wind velocity we have adopted the value given by Cerruti-Sola & Perinotto (1985).

In the case of He2-99, the effective stellar temperature is that estimated by Kaler et al. (1989), based on the Stoy method. The terminal wind velocity has also been taken from these authors. Our adopted distance is an average value including the estimates by Maciel (1984), Daub (1982) and Kaler et al. (1989).

He2-113 has the lowest extinction spectrum of our sample. The effective temperature is an average value of the determinations based on the H-Zanstra temperature and on the Stoy temperature. The terminal wind velocity is an adopted value, taken to be consistent with values observed in other low-temperature central stars. The distance has been estimated on the basis of our measured radial velocities of Na I interstellar lines and the galactic rotation curve of Gathier (1984)

For BD+30°3639 we have recalculated the H-Zanstra temperature based on our own data (de Freitas Pacheco et al. 1989). The distance has also been estimated from our measured radial velocity of interstellar NaI. The wind terminal velocity has been taken from Pwa, Pottasch & Mo (1986).

In the case of NGC 5315, the stellar temperature has been taken from de Freitas Pacheco, Codina & Viadana (1986). The distance has again been estimated from our interstellar NaI data and the wind terminal velocity has been derived from the half-widths at zero intensity of carbon lines.

Table 3 summarizes the main wind properties derived from our calculations, namely the average ionization fraction, the \( \text{C}/\text{He} \) ratio and the mass-loss rate. We note that the resulting ionization fractions for the different objects follow more or less the expected trend as a function of the excitation class of the star. The only exception seems to be \( \langle X/\text{C}^4 \rangle \) in He2-99, where we would expect a smaller value, taking into account the relatively low effective temperature of the central star. The value of the equivalent width due to C IV \( \lambda_{5806} \) seems to be abnormally large, but our measured value is consistent with the results of Kaler et al. (1989). It may be that the effective temperature of the star was underestimated, and a further investigation of this point is certainly necessary. The derived \( \text{C}/\text{He} \) ratios indicate that the surfaces of our sample stars have been contaminated by He-burned material. Moreover, the mass-loss rates are substantially higher than previous estimates for central stars having WC spectra (Hutsemekers & Surdej 1989).

Evolutionary sequences for central stars of planetary nebulae were calculated by Wood & Faulkner (1986). In some of their models, the nucleus of an AGB star evolves...
through the planetary nebula phase, burning helium and losing mass at an imposed rate of $3 \times 10^{-5} \, M_\odot \, yr^{-1}$. For their type B models, such a mass-loss rate is maintained until the residual hydrogen content of the star has been reduced to $10^{-9}$ by mass fraction. The remnant star has an enriched surface abundance and could be a representative model for our hydrogen-deficient central stars. However, the evolution along the horizontal portion of the track is so fast ($t_A \sim 300 \, yr$) that it conflicts with the estimated expansion age. If a lower mass-loss rate is adopted until the star has left the AGB, a final helium-shell flash may occur with a return to the AGB. In some evolutionary sequences calculated by Wood & Faulkner (1986), the star after leaving the AGB may reach high enough temperatures to ionize the surrounding nebula before the occurrence of the flash. Moreover, in this case the H-burning shell is never recovered and the remnant will enter the gravitational contraction phase directly from the post-flash helium burning. This scenario seems to be more appropriate for describing CSPN with WC spectra. On the other hand, evolutionary calculations have shown that the luminosities of AGB stars are determined essentially by the core mass. From the calculations by Wood & Faulkner (1986), the luminosity as a function of the remnant mass during the He-burning phase can approximately be given by

$$\frac{L}{L_\odot} = 71,430 \left( \frac{M_\odot}{M_\odot} \right) \left( M_{\odot} - 0.54 \right).$$

(14)

The resulting masses derived from this formula are given in Table 4. The calculated surface gravity and the N/O ratio derived for the associated nebula (de Freitas Pacheco & Costa 1991) are also given in Table 4.

The following points should be noted from inspection of Table 4. First, the progenitors of planetaries are intermediate-mass stars. Type II nebulae originate from progenitors with masses less than 3 $M_\odot$, and underwent the first dredge-up when the star was located at the base of the red giant branch. This episode produces a slight nitrogen enrichment at the surface. Type I nebulae are probably associated with more massive progenitors and have undergone successive dredge-up episodes. If the mass of the central star is correlated with the progenitor mass, we would expect the mass of the remnant star to also be correlated with the nitrogen enrichment of the associated nebula. Fig. 2 is a plot of CSPN mass versus N/O ratio for the nebulae. In spite of the uncertainties in the distances and consequently in the masses, there is a clear trend in the sense that nebulae with a high N/O ratio are associated with more massive stars. An analysis of this problem with a larger sample, including CSPN of different spectral types, is currently underway (Costa & de Freitas Pacheco, in preparation). The second point to be noted is as follows. Cerruti-Sola & Perinotto (1985) pointed out that the wind of a central star becomes weaker as the surface gravity increases. In order to check this point, we have plotted in Fig. 3 the mass-loss rate $\dot{M}$ as a function of the surface gravity. We notice a clear trend

<table>
<thead>
<tr>
<th>Object</th>
<th>$T_\star (K)$</th>
<th>D(kpc)</th>
<th>$R_*/R_\odot$</th>
<th>$L/L_\odot$</th>
<th>$T_\star (K)$</th>
<th>$V_\infty (km/s)$</th>
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<td>32000</td>
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<td>0.9</td>
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<td>1.8</td>
<td>3.16</td>
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<td>1200</td>
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<td>22300</td>
<td>3.1</td>
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<td>3.46</td>
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<td>1000</td>
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<tr>
<th>Object</th>
<th>$\langle X(He^+) \rangle$</th>
<th>$\langle X(He^{+2}) \rangle$</th>
<th>$\langle X(C^{+2}) \rangle$</th>
<th>$\langle X(C^{+3}) \rangle$</th>
<th>C/He</th>
<th>$\dot{M}(M_\odot yr^{-1})$</th>
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<tr>
<td>SwSt-1</td>
<td>0.754</td>
<td>0.245</td>
<td>0.667</td>
<td>0.084</td>
<td>0.41</td>
<td>$5.7 \times 10^{-7}$</td>
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<tr>
<td>He2-99</td>
<td>0.982</td>
<td>0.018</td>
<td>0.494</td>
<td>0.331</td>
<td>0.50</td>
<td>$4.0 \times 10^{-6}$</td>
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<td>-</td>
<td>0.971</td>
<td>0.0012</td>
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<td>0.948</td>
<td>-</td>
<td>0.315</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>0.41</td>
<td>$1.6 \times 10^{-6}$</td>
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<table>
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<tr>
<th>Object</th>
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<th>$\log g$</th>
<th>N/O (neb)</th>
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<tr>
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<td>NGC5315</td>
<td>0.60</td>
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Mass-loss rates are in the range $5.7 \times 10^{-7}$ to $6.7 \times 10^{-6}$ $M_\odot$ yr$^{-1}$. These values are substantially higher than previous estimates for central stars having WC spectra. The N/O ratios observed in the associated nebulae are correlated with the remnant masses. Such a correlation was expected, since more massive progenitors have undergone distinct dredge-up episodes. Moreover, mass-loss rates decrease with increasing surface gravity, in qualitative agreement with expectations from radiatively driven winds.

CSPN with WC spectra probably result from the removal of the H-rich envelope as a consequence of a late He-shell flash. The star returns to the AGB and evolves again along the horizontal portion of its track, burning helium before initiating the gravitational contraction phase.

ACKNOWLEDGMENTS

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APPENDIX

The departure coefficient $b_i$ from LTE of a given level $i$ can be calculated as follows. The statistical equilibrium of level $i$ of an ion in an ionization state $m$ is given by

$$n_i^m \sum_i \sum_i A_i \beta_i = \sum_i n_i^m T_i + \sum_i n_i^m A_i \beta_i + \alpha_i (T_i) n_i^{m+1}.$$  \hfill (A1)
In the above equation, the left-hand side gives the decay to the lower levels. The first term on the right-hand side gives the photoexcitation from the lower levels, the second term represents the decay from the upper levels and the third gives the recombination from the continuum. The $\beta_\gamma$ are the photon escape probabilities calculated within the Sobolev approximation, the $A_{\gamma\beta}$ are the transition probabilities, the $\alpha, \gamma$ are the recombination coefficients from the continuum and the photoexcitation rate is given by

$$\Gamma_\gamma = 4\pi \sigma_\gamma \frac{I_{\nu_\gamma}}{h \nu_\gamma} \beta_{\gamma\gamma}'$$  \hspace{1cm} (A2)$$

Here, $I_{\nu_\gamma}$ is the stellar radiation intensity at the transition frequency and $\beta_{\gamma\gamma}'$ is defined as

$$\beta_{\gamma\gamma}' = \int_{4\pi} \frac{\omega_\rho (1 - e^{-\tau_\gamma})}{\tau_\gamma} ~ d\omega_\rho,$$  \hspace{1cm} (A3)$$

where the integration is performed over the solid angle subtended by the star at the point under consideration.

For collisions to dominate over radiative excitation, we need

$$\frac{8.63 \times 10^{-6} \Omega}{c \tau_{e}^{1/3} \epsilon} \exp(-h\nu/kT_{e}) \frac{N_e}{B_{\infty}} U_{e}^*(r),$$  \hspace{1cm} (A4)$$

where $\omega_\rho$ is the statistical weight of the lower level, $\Omega$ is the collision strength for the transition 1$\rightarrow$u, $B_{\infty}$ is the Einstein coefficient for photoexcitation and $U_{e}^*(r)$ is the stellar radiation density at a distance $r$ from the star, calculated within the Sobolev approximation. The above condition imposes a minimum mass-loss rate above which collisions dominate (see, for example de Freitas Pacheco, Gilr & Pottasch 1982):

$$\dot{M} > 1.04 \times 10^{-4} \left[ 1 + 3A \right] \frac{I_{\nu_e} \Omega}{\epsilon} \frac{10^{-6} \Omega}{c \tau_{e}^{1/3} \epsilon} V R^2 \beta_{\infty} \tau_{e}^{1/2} \exp(h\nu/kT_{e}),$$  \hspace{1cm} (A5)$$

where $\dot{M}$ is in $M_\odot$ yr$^{-1}$, $V$ is in km s$^{-1}$, $R$ is in $R_\odot$ and $I_{\nu_e}$ is the radiation flux at the stellar surface in erg cm$^{-2}$ s$^{-1}$ $\AA^{-1}$. The other symbols have already been defined. With the stellar parameters given previously and typical atomic parameters for the lines under consideration, the critical mass-loss rate is about $10^{-3} M_\odot$ yr$^{-1}$ in most cases. This justifies neglecting electron collisions in the statistical equilibrium equations.

If we substitute equation (6) into equation (15), we obtain

$$\sum b_i g_i F(T_e) \exp(I_i/kT_e) \Gamma_\gamma + \sum b_j g_j F(T_e) \exp(I_j/kT_e) A_{\gamma\beta} \alpha_{ij}(T_e) \frac{b_i}{g_i F(T_e) \exp(I_i/kT_e) \sum A_{\gamma\beta} \alpha_{ij}(T_e)}.$$  \hspace{1cm} (A6)$$

This equation can be solved by successive iterations, assuming that initially the $b_j$s are equal to 1 (the LTE value). The transition probabilities and the photoionization cross-sections from level $i$ used to calculate the recombination coefficients have been taken from files of the Opacity Project. For C II we take an atomic model consisting of the continuum and three levels (2s$^2$2f, 2s$^2$3d and 2s$^2$2). For C III we consider the continuum and the levels 4d$^2$D, 3p$^3$P$^0$, 3s$^3$S and 2p$^3$P$^0$, while for C IV, besides the continuum, we take into account the levels 5d$^2$F$^0$, 4d$^2$D, 3p$^3$P$^0$, 3s$^3$S, 2p$^3$P$^0$ and 2s$^3$S. For He II we consider a 10-level atom and for He I we consider, besides the continuum, the levels 3s$^3$S, 3p$^3$P$^0$ and 2s$^3$S of the triplet series, since we are interested mainly in the transition He I $\lambda$5876. Table A1 gives the calculated recombination coefficients for the different C ions and levels.

<table>
<thead>
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<th>Ion</th>
<th>level</th>
<th>$\alpha(10^{-18} \text{cm}^2 \text{s}^{-1})$</th>
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</tr>
<tr>
<td>CII</td>
<td>2s$^2$3d</td>
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</tr>
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<td>4d$^2$D</td>
<td>4.91</td>
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<td>3p$^3$P$^0$</td>
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</tr>
<tr>
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<td>3s$^3$S</td>
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