Ultraviolet spectra of planetary nebulae — IX. High-dispersion observations of NGC 7662

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Received 1982 July 7

Summary. High-dispersion IUE spectra of NGC 7662 have been obtained with exposure times optimized for measurement of the relative strengths of the components of: CIV $\lambda 1548$, 1551; CIII $\lambda\lambda 1907, 1909$ and [NeIV] $\lambda\lambda 2422, 2424$. The CIV ratio ($\lambda 1548$)/($\lambda 1551$) is expected to be 2.00, the ratio of the statistical weights of the emitting levels, and the observed value is $1.92 \pm 0.15$. The CIII and [NeIV] ratios depend upon the electron density, $N_e$, and from the observations it is concluded that $N_e$ for NGC 7662 is in the range 1300 to 4000 cm$^{-3}$. The presence of the dielectronic recombination line CIII $\lambda 2297$ is established beyond doubt. The absolute calibration of IUE high-dispersion spectra is also discussed.

1 Introduction

High-dispersion ultraviolet observations of planetary nebulae, which can be obtained using IUE, are of interest for the following reasons. (i) The intensity ratios CIII($\lambda 1907$)/($\lambda 1909$) and [NeIV]($\lambda 2422$)/($\lambda 2424$) can be measured in high-dispersion spectra and depend upon the electron density (Nussbaumer & Schild 1979; Flower, Nussbaumer & Schild 1979; Lutz & Seaton 1979). (ii) High dispersion gives improved contrast between emission lines and background continua and hence enables weaker lines to be detected (Clavel, Flower & Seaton 1981; Adams & Seaton 1982). (iii) Using high dispersion one can discriminate between narrow nebular emission lines and broader features associated with the spectra of the central stars (Harrington & Feibelman 1982).

A detailed study of the planetary nebula NGC 7662 has been made by Harrington et al. (1982) who give results obtained from low-dispersion IUE observations, and use results from the high-dispersion observations reported in the present paper for the CIII and [NeIV] intensity ratios. Since the IUE cameras have a rather limited dynamic range, well-chosen exposure times were required to obtain accurate measurements. An important check on the accuracy of the measurements, and on the correctness of the model of Harrington et al., is provided by measurements of the relative strengths of the components of the CIV resonance doublet. For collisional excitation the intensity ratio ($\lambda 1548$)/($\lambda 1551$) = 2.00, the ratio of
statistical weights of the upper levels. Some observations of planetary nebulae have given \( \text{CIV} \) ratios different from 2.00 (Nussbaumer & Schild 1981; Flower et al. 1979; Köppen & Wehrse 1980) and Peimbert (1980) has suggested that the discrepancies may be due to dust absorption. Harrington et al. give reasons for believing that about 70 per cent of the \( \text{CIV} \) radiation produced in NGC7662 is absorbed by dust. They find that the scattering optical depths are \( \tau_S \approx 2 \times 10^4 \) for \( \lambda 1549 \) and \( \tau_S \approx 1 \times 10^4 \) for \( \lambda 1551 \). Using the results of Hummer & Kunasz (1980), who solved the transfer problem, they show that 70 per cent of the \( \text{CIV} \) radiation will be absorbed if the dust optical depth is \( \tau_D = 0.1 \), and with that value of \( \tau_D \) they are able to account for the observed thermal infrared emission. Solutions of the transfer problem show, however, that the amount of absorption by dust is insensitive to the exact value of \( \tau_S \) and that, for typical conditions in planetary nebulae, dust absorption will not cause the \( (\lambda 1548)/(\lambda 1551) \) ratio to differ significantly from 2.00.

The objectives of the work on NGC7662 described in the present paper were: (i) to make an accurate measurement of the \( \text{CIV} (\lambda 1548)/(\lambda 1551) \) ratio; (ii) to measure the density-sensitive \( \text{CIII} \) and \( \text{NeIV} \) ratios (the latter to an accuracy better than that achieved by Lutz & Seaton 1979); (iii) to assess the accuracy of the absolute calibration of \( \text{IUE} \) high-dispersion spectra for extended sources.

A main objective in the work of Lutz & Seaton (1979) was to measure the wavelengths of the \( \text{NeIV} \) lines. The \( \text{IUE} \) small slot (3 arcsec diameter) was used because it gives better resolution for an extended source and because at that time (1978 June) software had not been developed for the extraction of large-slot data for extended sources. Improved \( \text{NeIV} \) wavelengths have subsequently been obtained by Penston et al. (1982) from observations of RR Tel. Their results, \( \lambda (\text{air}) = 2421.69 \pm 0.05 \, \text{Å} \) for \( 2D^0_{3/2} \rightarrow 4S^0 \), and \( 2424.23 \pm 0.05 \, \text{Å} \) for \( 2D^0_{5/2} \rightarrow 4S^0 \), are smaller than those of Lutz & Seaton by 0.15 Å (the improvement results from the use of more lines for the correction of dispersion constants).

2 \( \text{IUE} \) observations and data reduction

All \( \text{IUE} \) observations reported in the present paper were obtained using high dispersion and the large slot (10 x 23 arcsec oval). A short-wavelength spectrum, SWP9998, was obtained on 1980 September 3 with an exposure of 25 min, optimized for measurement of the \( \text{CIV} \) lines. A long-wave spectrum, LWR6805, obtained on 1980 January 28 with an exposure time of 120 min, gave a few pixels to be saturated in \( \text{NeIV} \) \( \lambda 2424 \) and a shorter exposure, LWR8000 57 min, was therefore obtained on 1980 June 10.

For high-dispersion observations the long axis of the \( \text{IUE} \) large slot is in the direction of the dispersion. The 10 arcsec width of the slot is such as to cause problems of order overlap when one observes extended sources and there is strong continuum emission. This problem, which is discussed by Clavel et al. (1981) in connection with observations of IC 418, does not arise in our work on NGC7662 since the continuum is sufficiently weak.

The data were extracted using procedures described by Giddings (1981) and implemented on the UCL node of the STARLINK system. The flux-number data are displayed and the position of the extraction window is chosen to be such that all of the flux in each spectrum line is included. The GPHOT image is examined for possible contamination in the extraction window by particle spikes, fiducial marks and emission from lines in adjacent orders. Image defects occurring in the regions adopted for the instrument background are removed in the procedure for calculating a smoothed background.

The flux number in a spectrum line (\( \text{FN} \, \text{s}^{-1} \)) is denoted by \( n_\lambda \) for low dispersion and \( N_\lambda \) for high dispersion. The absolute fluxes are given by

\[
F(\lambda) = n_\lambda S_\lambda^{-1}
\]
for low dispersion, where $S^{-1}$ is the inverse sensitivity function of Bohlin et al. (1980), and by

$$F(\lambda) = N_{\lambda} C_{\lambda} S_{\lambda}^{-1}$$

(2.2)

for high dispersion, where $C_{\lambda} = n_{\lambda}/N_{\lambda}$. For two lines close in wavelength we have $F(\lambda_1)/F(\lambda_2) = N_{\lambda_1}/N_{\lambda_2}$.

3 Measurement of the flux ratios

Table 1 gives measured values of $N_{\lambda}$ for the [C IV, C III] and [Ne IV] lines.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>$\lambda$ (Å)</th>
<th>$N_{\lambda}$ (FN s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV</td>
<td>$2p^2 P^0_{3/2} - 2s^2 S_{3/2}$</td>
<td>1548.20</td>
<td>22.7</td>
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<tr>
<td></td>
<td>$2p^2 P^0_{1/2} - 2s^2 S_{1/2}$</td>
<td>1550.77</td>
<td>11.8</td>
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<tr>
<td>C III</td>
<td>$2s^2 P^0_{3/2} - 2s^2 S_{1/2}$</td>
<td>1906.68</td>
<td>6.43</td>
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<tr>
<td></td>
<td>$2s^2 P^0_{1/2} - 2s^2 S_{1/2}$</td>
<td>1908.73</td>
<td>4.43</td>
</tr>
<tr>
<td>[Ne IV]</td>
<td>$2p^3 P^0_{3/2} - 2p^3 S^0_{3/2}$</td>
<td>2421.69</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>$2p^3 P^0_{1/2} - 2p^3 S^0_{1/2}$</td>
<td>2424.23</td>
<td>13.9</td>
</tr>
</tbody>
</table>

* $\lambda$(vac) for C IV, C III], and $\lambda$(air) for [Ne IV].

3.1 THE C IV DOUBLET

Our measurements gave the flux ratio $F(\lambda 1548)/F(\lambda 1551) = 1.92 \pm 0.02$ with error estimate based on consideration of noise. Allowing for possible systematic errors in the Intensity Transfer Function and the ripple correction, our estimate for the ratio is

$$F(\lambda 1548)/F(\lambda 1551) = 1.92 \pm 0.15$$

(3.1)

This is consistent with predictions which we believe to be reliable and gives us confidence in the accuracy of other measured ratios.

3.2 THE C III] LINES

The C III] lines, $\lambda\lambda 1907$ and 1909, are observed in both SWP and LWR spectra. In the vicinity of these lines the SWP camera has the higher sensitivity but the disadvantage that the lines come close to the edges of diffraction orders. There is no such disadvantage for LWR which is therefore to be preferred if the exposure time is sufficiently large, which is the case for LWR 6805. Measurements gave

$$F(\lambda 1907)/F(\lambda 1909) = 1.45 \pm 0.15$$

(3.2)

(where the uncertainties in the ripple correction and the intensity transfer function are included in the error) which is close to the low-density limit of the ratio as a function of electron density, as calculated by Nussbaumer & Schild (1979). From (3.2) we can therefore obtain only an upper limit to the electron density, $N_e < 4000$ cm$^{-3}$.

3.3 THE [Ne IV] LINES

Measurements for [Ne IV] from LWR 8000 gave

$$F(\lambda 2424)/F(\lambda 2422) = 1.2 \pm 0.1.$$
The longer exposure, LWR 6805, gave close agreement with LWR 8000 for $F(\lambda 2422)$ but an error of about 17 per cent in $F(\lambda 2424)$ due to slight saturation. The present value of 1.2 for the [Ne IV] ratio is more accurate than the value of 0.9 obtained by Lutz & Seaton.

We interpret the ratio using improved collision strengths of Giles (1981) and transition probabilities of Zeippen (1982). With an electron temperature of $T_e = 14500$ K from Harrington et al. (1982) we obtain from (3.3) for $N_e$ in cm$^{-3}$

$$1300 < N_e < 4000 \quad (3.4)$$

which is consistent with the result obtained from C III].

4 The absolute calibration of high-dispersion spectra

Cassatella, Ponz & Selvelli (1981) give values of $C_\lambda = n_\lambda/N_\lambda$ from measurements of emission-line fluxes observed at low and high resolution, and interpolate smooth curves of $C_\lambda$ against $\lambda$. They consider objects which are effectively point sources. We consider the use of their calibration for an extended source. Table 2 compares fluxes $F(\lambda)$ obtained from our high-resolution LWR spectra of NGC 7662 with those obtained from the low-resolution observations of Harrington et al. (1982). It is seen that, for the stronger lines, low- and high-resolution agree to within 20 per cent.

The C III] dielectronic recombination line, $2p^2 \, ^1D \rightarrow 2s \, 2p \, ^1P^0 \lambda 2297$, plays a key role in the analysis of Harrington et al. It is gratifying that the high-dispersion observations place the identification beyond doubt. The value of $F(\lambda 2297)$ observed at high dispersion is consistent with previous measurements of blended features at low dispersion.

The high-dispersion spectra have a lot of noise in the region of [O III] $\lambda 2321$ and of the C II] multiplet $\lambda \lambda 2323.5, 4.7, 5.4, 6.9$ and 8.1. The strongest C II] component is $\lambda 2325.4$ and its measured flux was $F(\lambda 2325.4) = 1.1$ (using units $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ as in Table 2). Use of the relative strengths of the components from Adams & Seaton (1982) gives $F(C II]) = 2.2$ in satisfactory agreement with $F(C II]) = 2.9 \pm 0.5$ estimated by Harrington et al. The agreement is less satisfactory for [O III] $\lambda 2321$, for which the high-dispersion observations gave $F(\lambda 2321) = 1.6$ compared with $F(\lambda 2321) = 0.7$ estimated from the

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$</th>
<th>$F(\lambda)$, $10^{-13}$ erg cm$^{-2}$ s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>O III</td>
<td>3133</td>
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<tr>
<td>O III</td>
<td>3048</td>
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<tr>
<td></td>
<td>3036</td>
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<td></td>
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<td>3024</td>
<td>1.9</td>
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<tr>
<td>[A IV]</td>
<td>2869</td>
<td>0.6</td>
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<tr>
<td></td>
<td>2854</td>
<td>0.9</td>
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<tr>
<td>O III</td>
<td>2837</td>
<td>4.2</td>
</tr>
<tr>
<td>He II</td>
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<td>4.6</td>
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<tr>
<td>He II</td>
<td>2512</td>
<td>2.3</td>
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<tr>
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<td>2422, 2424</td>
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<tr>
<td>He II</td>
<td>2386</td>
<td>1.4</td>
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<tr>
<td>He II</td>
<td>2307</td>
<td>0.7</td>
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<tr>
<td>C III</td>
<td>2297</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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strength of [O III] \( \lambda 4363 \) and a known branching ratio. The estimate of \( F(\lambda 2321) \) from the \( (\lambda 2321)/(\lambda 4363) \) branching ratio should be reliable; the discrepancy with the measured value of \( F(\lambda 2321) \) illustrates the errors which can arise in making measurements in noisy regions of IUE high-dispersion spectra.

5 Conclusions

(i) For C IV \( \lambda 1548 \), 1551 produced by collisional excitation in the envelopes of planetary nebulae the ratio of observed fluxes, \( F(\lambda 1548)/F(\lambda 1551) \), is expected to be close to 2.0. Accurate measurements of the ratio, using IUE, require well-chosen exposure times and care in data extraction. We have made such measurements for NGC 7662 and obtain a ratio equal to 2.0 to within 5 per cent.

(ii) From C III \( (\lambda 1907)/(\lambda 1909) \) and [Ne IV] \( (\lambda 2422)/(\lambda 2424) \) we conclude that \( 1300 < N_\alpha < 4000 \) in NGC 7662.

(iii) Absolute fluxes from high- and low-resolution spectra of NGC 7662 agree to within 20 per cent for the stronger lines.

(iv) The identification of C III \( \lambda 2297 \) is established beyond doubt.

Acknowledgments

We thank Dr Jack Giddings for his generous help with data processing. The IUE observations were obtained at the VILSPA Tracking Station of the European Space Agency and we thank the VILSPA staff for their assistance. CJP acknowledges the financial support of the SERC.

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