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O IV TEMPERATURE DETERMINATION FOR NGC 7662

M. A. SHURE, T. HERTER, AND J. R. HOUCK
Cornell University
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ABSTRACT

Our present theoretical understanding of the processes leading to thermal balance in the He III zone of planetary nebulae indicates that they differ markedly from those outside. They suggest higher temperatures within this inner, high-excitation region. Observational tests of the predicted temperature within these zones are scarce. The most common determinant, the [O III] 4363 Å/(4959+5007) Å line ratio, yields temperatures outside the He III zone.

We present a new method for the determination of electron temperatures in high-excitation zones of planetary nebulae and active galactic nuclei. The present study uses the ratio of the O IV line at 25.87 μm to those near 1400 Å to calculate a temperature within the He III zone of NGC 7662. The observed fluxes yield a lower bound to the temperature of 14,730 K. This is significantly higher than the O III temperature of $\sim$12,000 K.

Subject headings: galaxies: nuclei — nebulae: planetary — ultraviolet: spectra

I. INTRODUCTION

Theoretical studies have shown that thermal balance processes in the central region of high-excitation planetary nebulae are quite different from those taking place farther from the central star or in H II regions (Hummer and Seaton 1964; Flower 1969; Harrington *et al.* 1982). Planetary nebulae, unlike H II regions, possess an He III zone because of their high-temperature central stars. Within this high-excitation region of the nebula, hydrogen is kept ionized in large part by He III recombination radiation. The main coolant is the C IV 1549 Å line, while the [O III] 5007 and 4959 Å lines dominate cooling in the gas at larger radii. Observational determinations of temperatures within the He III zone would help test our understanding of the physical processes taking place there.

Measurements of He III zone temperatures are relatively scarce. A common thermometer for planetary nebulae has been the 4363 Å/(4959+5007) Å line ratio of O III. The ionization potential of O III is 55 eV. Since the ionization potential of He II is 54 eV, O III will be found mainly outside the He III zone. A dominant state of ionization in the He III zone will be O IV. Therefore, O IV should be an appropriate probe of the He III zone.

The lowest five energy levels of the O IV ion are shown in Figure 1 (Bromander 1970). The next level, at 15.8 eV, and all higher levels are ignored. The 25.87 μm IR line originates in transitions between the $2s^2 2p(^2P_{1/2,3/2})$ levels. The $2s2p^2(^4P_{1/2,3/2,5/2})$ levels result in five UV emission lines from transitions to the ^2P levels (the $J=5/2 \rightarrow 1/2$ transition is forbidden). These lines are clustered near 1400 Å and will be referred to below simply as the "1400 Å lines." If the ^2P and ^4P levels are excited by electron collisions, as is assumed here, the large energy difference between the ^2P and ^4P multiplets makes the IR-to-UV line flux ratio a sensitive temperature indicator (Shure *et al.* 1983*a*). The predicted variation of this ratio with nebular density and temperature is shown in Figure 2. These calculations are discussed later.

An unfortunate blending of two Si IV lines at 1393.8 and 1402.8 Å with the O IV] 1400 Å lines makes high-resolution UV observations necessary to resolve the lines and obtain an accurate O IV] line flux. In high-dispersion mode, the *International Ultraviolet Explorer* (*IUE*) satellite is capable of such resolution. The O IV]+Si IV blend has been resolved in NGC 7662 by a high-dispersion spectrum obtained by Heap (1979).

II. OBSERVATIONS

[O IV] 25.87 μm line fluxes for five planetary nebulae have been obtained from observations using NASA's Kuiper Airborne Observatory (KAO) (Shure *et al.* 1983*b*). These nebulae are IC 2003, NGC 2392, 7027, 7354, and 7662. The fluxes were obtained with an instrumental beam covering the entire [O IV] emission region in all of these nebulae. The flux from NGC 7662 is $(5.14 \pm 0.20) \times 10^{-17}$ W cm^{-2}.

The O IV]+Si IV 1400 Å line blend has been observed in all of these nebulae except NGC 7354 using the *IUE* spectrometer in low-dispersion mode. In addition, a high-dispersion, large-aperture spectrum of NGC 7662 obtained by Heap (1979) is available. This spectrum

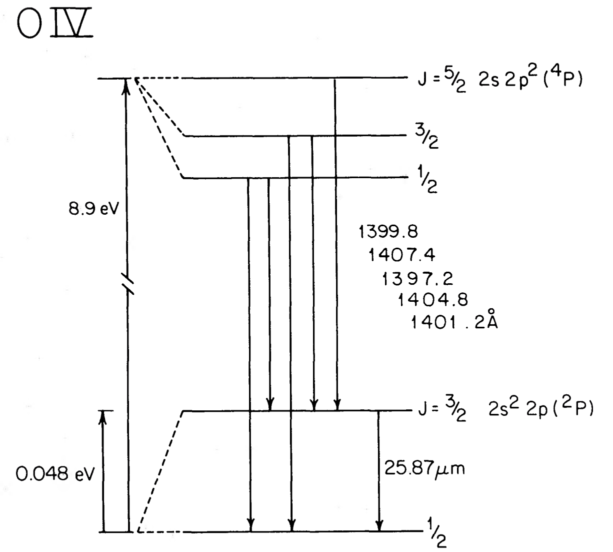

FIG. 1.—Lowest five energy levels of O IV and associated transitions. The energy scale within the ^2P and ^4P levels has been expanded.

resolves the O IV] and Si IV lines, allowing this blend to be separated. The Si IV lines were found to contribute 12% of the blend. The resulting sum of the O IV] line fluxes is $(2.4 \pm 0.3) \times 10^{-18}$ W cm^{-2} after correction for extinction using an Hβ extinction constant of $c = 0.23 \pm 0.05$ (Harrington *et al.* 1982) and the UV extinction curve of Seaton (1979). These imply an extinction of 1.3 ± 0.3 mag at 1400 Å.

III. NEBULAR TEMPERATURE FROM O IV LINES

The high-dispersion spectrum of NGC 7662 was taken with the larger of the two *IUE* entrance apertures. This

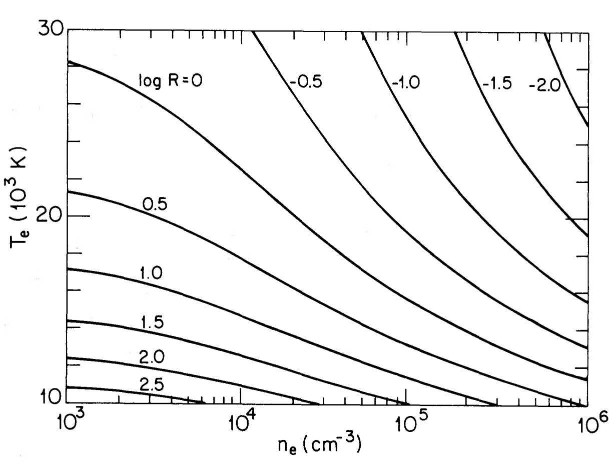

FIG. 2.—Contour plot of R, the ratio of emissivity in the 25.87 μm line to the emissivity in the 1400 Å lines, for O IV as function of electron density and temperature.

large aperture subtends a 10".3 × 23".0 oval on the sky (Bohlin *et al.* 1980). The close match between the ionization potentials of He II and O III suggests that the outer boundary of line emission from the He III region of a nebula should coincide with that of the O IV region. The isophote map of Coleman, Reay, and Worswick (1976) shows that He II 4686 Å emission (due to recombined He III ions) in NGC 7662 has a roughly circular form and extends to approximately 14" in diameter.[1] Since the O IV region will extend this far out, the *IUE* large aperture does not cover the O IV region entirely. Harrington *et al.* (1982) have numerically integrated the 4686 Å intensity contours of Coleman *et al.* over the *IUE* large-aperture outline and found that it includes 68% of the emission. In order to correct for the partial coverage of the O IV region, the O IV] flux obtained with the *IUE* large aperture was multiplied by $(0.68)^{-1}$ to yield an estimate of the total O IV] 1400 Å line flux from the nebula. It is this total flux that must be compared with the IR flux, since the latter was obtained from the entire nebula using a 30" beam. The resulting ratio of the 25.87 μm flux to the corrected total flux of the 1400 Å lines is 14.6 ± 1.9 (1 σ errors). This ratio is an upper limit to the actual IR-to-UV flux ratio for the following reason: Although the He II 4686 Å emission will fill the entire sphere of the He III zone, a substantial portion of the oxygen ions within this volume may exist in ionization stages higher than O IV. The comprehensive model of NGC 7662 constructed by Harrington *et al.* (1982) suggests that the ratio of the total number of oxygen ions ionized above O IV to O IV is 0.59. Therefore, the O IV emission will originate in a shell bounded on the inside by the O V zone. Using the same aperture correction factor as for the filled emission sphere of He II 4686 Å overestimates the fraction of emission from the shell passed by the *IUE* large aperture. The estimate of the total O IV] 1400 Å emission from the nebula using a correction factor of $(0.68)^{-1}$ will then be a lower bound to the actual total. However, the O IV temperature derived from the IR/UV flux ratio is fairly insensitive to inaccuracies in the fluxes. Even a factor of 2 increase in the UV flux only results in a temperature increase of ~1900 K from the values obtained below.

Excitation of both the IR and UV levels of the O IV ions was assumed to occur only through electron collisions. De-excitation can occur through radiative decay or collisional de-excitation. The latter process only becomes important at densities above $\sim 10^4$ cm^{-3} for an assumed temperature of 10^4 K (Shure *et al.* 1983*b*). By balancing processes into and out of each of the five levels of O IV, the emissivities of the IR and UV lines were calculated as a function of n_e and T_e. The relevant

[1]The scale of the map of Coleman, Reay, and Worswick has been corrected in accordance with a private communication from Reay mentioned by Harrington *et al.* (1982).

collision strengths and transition probabilities were taken from the compilation of Mendoza (1983). The collision strengths given there were calculated by M. A. Hayes (Hayes and Nussbaumer 1983). They are the results of recent calculations including resonance contributions to the collision strength and so are probably an improvement over previous values. The small temperature dependence of the collision strengths was ignored, and the values at 10^4 K were used. The resulting values of the IR-to-UV line emissivity ratio are shown in Figure 2 as a contour plot in (n_e, T_e)-space.

The region of the (n_e, T_e)-plane covered by the IR-to-UV line ratio estimate for NGC 7662 is shown in Figure 3. In order to estimate the nebular temperature, it is necessary to obtain at least rough bounds on the density. A recent measurement of the [Ne IV] 2422 to 2424 Å line ratio yields an electron density of $1300 \leq n_e \leq 4000$ cm^{-3} (Flower, Penn, and Seaton 1982). We will adopt a density of 2650 ± 1350 cm^{-3}. This density should be appropriate to the O IV region since Ne IV exists within a range of ionization energies which largely overlaps that of O IV ($54.9 \leq$ O IV ≤ 77.4 eV and $63.4 \leq$ Ne IV ≤ 97.1 eV). The electron temperature range corresponding to the IR-to-UV flux ratio of 14.6 ± 1.9 and density 2650 ± 1350 cm^{-3} is $T_e = 15{,}450^{+910}_{-720}$ K. It must be remembered that since the corrected UV flux is a lower bound, owing to the uncertain aperture correction, this temperature is a lower limit to the actual value.

An [O III] temperature contour map of NGC 7662 (Reay and Worswick 1982) indicates a median temperature (defined as the temperature of the contour above which half of the nebula is covered) of ~12,000 K and includes contours of up to 13,500 K near the center. Since O III exists outside the He III zone under lower excitation conditions, it is reasonable that T_e (O III) < T_e (O IV). Our result is also consistent with the lower limit to T_e (O IV) obtained by Harrington, Lutz, and Seaton (1979) and Harrington *et al.* (1982) from *IUE* measurements of the O IV] 1400 Å lines and the He II 1640 Å line. Their result was 14,100 K.

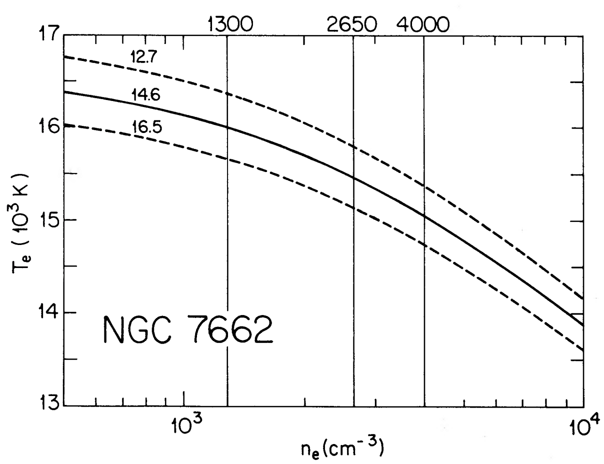

FIG. 3.—Contours of ratio of observed [O IV] 25.87 μm line flux to O IV] 1400 Å line flux for NGC 7662. One sigma errors are shown. This ratio has been corrected for extinction and partial coverage by *IUE* aperture (see text). Also shown is the density estimate of 2650 ± 1350 cm^{-3} from the [Ne IV] line ratio.

From the results of their numerical model of NGC 7662, Harrington *et al.* tabulated a quantity T_0 (n_{ij}) which is defined as

$$T_0\,(n_{ij}) = \frac{\int n_e n_{ij} T_e r^2\,dr}{\int n_e n_{ij} r^2\,dr}, \qquad (1)$$

where n_{ij} is the number density of ions of element i in ionization state j. For O IV their model predicts T_0 (O IV) = 14,580 K. Since the collisional excitation of the O IV] UV lines involves temperature-sensitive Boltzmann factors, emission will be exponentially weighted toward higher temperature portions of the O IV zone. Harrington *et al.* (1982) find from their model that the temperature increases rapidly with decreasing radius within the He III zone, rising from 13,000 K at the outer boundary to 25,000 K near the center. We would therefore expect to find T_e (O IV, IR/UV determination) > T_0 (O IV), as is the case.

Another pair of lines that can be used for temperature estimates in the high-excitation regions of planetary nebulae are the 24.28 μm and 3426 Å lines of Ne V. The ratio of integrated fluxes for the lines was used by Shure *et al.* (1983*b*) to determine an electron temperature for NGC 7662. The result was T_e (Ne V) = $11{,}200^{+2000}_{-1100}$ K, in disagreement with theoretical models which predict T_e (Ne V) ~ 16,000–20,000 K. This low temperature was the result of interpreting the Ne V line ratio using ^3P_J–$^3P_{J'}$ collision strengths calculated by Saraph, Seaton, and Shemming (1969), which neglect excitation resonances. Recently, these collision strengths have been calculated with resonances included (Aggarwal 1983). The new values are roughly an order of magnitude greater than before, significantly raising the derived electron temperature. As a result of low-energy resonance structure in these collision strengths, the associated excitation rates are also temperature dependent. Using the [Ne V] 24.28 μm to 3426 Å line ratio and these new collision strengths yields T_e (Ne V) = $18{,}900^{+6400}_{-3500}$ K, assuming $n_e = 2650 \pm 1350$ cm^{-3}. Although a more accurate result awaits a better determination of the integrated 3426 Å flux, this is well within the theoretically predicted range of temperatures.

IV. DISCUSSION

A value of the electron temperature in the O IV region of NGC 7662 has been obtained from the ratio of the [O IV] 25.87 μm to the O IV] 1400 Å lines. The result is

$15{,}450^{+910}_{-720}$ K. As discussed earlier, this T_e (O IV) may be a lower bound to the actual value. Even so, the result indicates a substantially higher value of T_e within the he III zone than outside, as evidenced by T_e (O III) results of $\sim 12{,}000$ K.

A model value of 14,580 K is obtained by Harrington *et al.* (1982) from an integration linearly weighted in temperature over the O IV region. The O IV UV line emission is exponentially weighted toward higher temperature portions of the O IV zone, and so the result from the IR-to-UV line ratio is expected to be higher than the linearly weighted value.

It is tempting to compare the Ne V temperature of $18{,}900^{+6400}_{-3500}$ K to the O IV temperature and infer a higher temperature in the Ne V regions. However, since our O IV temperature is a lower bound, it is not clear that the temperature in the O IV regions is less then T_e (Ne V).

This O IV IR-to-UV line ratio method can be used to determine temperatures for other nebulae. The 25.87 μm flux has been measured for the planetary nebulae IC 2003, NGC 2392, 7027, and 7354. However, interstellar extinction and the limiting sensitivity of the *IUE* spectrometer in high-dispersion mode make observation times too long for all but NGC 7027. Differential extinction over the face of NGC 7027 would make correction of an observed O IV UV flux very difficult. We are presently searching for *IUE* high-dispersion spectra of planetary nebulae in which the O IV UV lines show up, as a basis for future 25.87 μm observations.

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REFERENCES

Aggarwal, K. M. 1983, *J. Phys. B.*, **16**, in press.
Bohlin, R. C., Holm, A. V., Savage, B. D., Snijders, M. A. J., and Sparks, W. M. 1980, *Astr. Ap.*, **85**, 1.
Bromander, J. 1970, *Ark. Fys.*, **40**, 257.
Coleman, C. I., Reay, N. K., and Worswick, S. P. 1976, *Advances Electronics Electron Phys.*, **40B**, 817.
Flower, D. R. 1969, *M.N.R.A.S.*, **146**, 171.
Flower, D. R., Penn, C. J., and Seaton, M. J. 1982, preprint.
Harrington, J. P., Lutz, J. H., and Seaton, M. J. 1979, in *The First Year of IUE*, ed. A. J. Willis (London: University College London), p. 199.
Harrington, J. P., Seaton, M. J., Adams, S., and Lutz, J. H. 1982, *M.N.R.A.S.*, **199**, 517.
Hayes, M. A., and Nussbaumer, H. 1983, preprint.
Heap, S. R. 1979, unpublished spectrum (*IUE* image no. SWP 4106).
Hummer, D. G., and Seaton, M. J. 1964, *M.N.R.A.S.*, **127**, 217.
Mendoza, C. 1983, in *IAU Symposium 103, Planetary Nebulae*, ed. D. R. Flower (Dordrecht: Reidel).
Reay, N. K., and Worswick, S. P. 1982, *M.N.R.A.S.*, **199**, 581.
Saraph, H. E., Seaton, M. J., and Shemming, J. 1969, *Phil. Trans. Roy. Soc. London A*, **264**, 77.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 73P.
Shure, M. A., Herter, T., Houck, J. R., Briotta, D. A., Jr., Forrest, W. J., Gull, G. E., and McCarthy, J. F. 1983*a*, in *IAU Symposium 103, Planetary Nebulae*, ed. D. R. Flower (Dordrecht: Reidel).
———. 1983*b*, *Ap. J.*, **270**, 645.

T. HERTER, J. R. HOUCK, and M. A. SHURE: Department of Astronomy, Cornell University, Ithaca, NY 14853-0352