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T_e-FLUCTUATIONS AND N^+/O^+ IN THE ORION NEBULA [1]

R. H. Rubin[2,3], R. J. Dufour[4], G. J. Ferland[5], P. G. Martin[6], J. A. Baldwin[7], J. J. Hester[8], and D. K. Walter[9]

RESUMEN

Usando el espectrógrafo de objetos débiles (FOS) en el *Telescopio Espacial Hubble*, medimos el flujo de las líneas de N II] ($2s2p^3\ ^5S_2 \rightarrow 2s^22p^2\ ^3P_{2,1}$) a $\lambda_{vac} = 2143.45$, 2139.68 Å en la Nebulosa de Orión. Para poder determinar el cociente N^+/O^+, también hemos medido el flujo de líneas del [O II] ($2p^3\ ^2P^0_{1/2,3/2} \rightarrow 2p^3\ ^4S^0_{3/2}$) a $\lambda_{vac} =$ 2471.05, 2471.12 Å. Además, con el FOS, fueron medidas otras líneas de emisión en la misma apertura para poder evaluar la temperatura electrónica promedio y la variación promedio de la temperatura al cuadrado (t^2) en la región de N^+ así como el cociente N^+/O^+. Cuando requerimos que los valores empíricamente determinados sean iguales para $(N^+/O^+)_{uv}$ (derivados de las líneas de [O II] 2471 y N II] 2142) y $(N^+/O^+)_{opt}$ (derivado de las líneas de [O II] 3728 y de [N II] 6585), obtenemos lo siguiente. Para la zona (N^+, O^+), la densidad electrónica promedio es $\sim 7\,000$ cm^{-3}, la temperatura electrónica promedio es 9500 K, t^2 es 0.032 y N^+/O^+ es 0.14. Para poder obtener N/O, el valor de N^+/O^+ empíricamente derivado requiere de una corrección que incluye la posibilidad de que las regiones de N^+ y O^+ no sean idénticas.

ABSTRACT

Using the Faint Object Spectrograph (FOS) on the *Hubble Space Telescope*, we measured the flux of the N II] ($2s2p^3\ ^5S_2 \rightarrow 2s^22p^2\ ^3P_{2,1}$) lines at $\lambda_{vac} = 2143.45$, 2139.68 Å in the Orion Nebula. In order to assess the N^+/O^+ ratio, we also measured the flux of the [O II] ($2p^3\ ^2P^0_{1/2,3/2} \rightarrow 2p^3\ ^4S^0_{3/2}$) lines at $\lambda_{vac} = 2471.05$, 2471.12 Å. In addition, with the FOS, other emission lines were measured in the same aperture in order to assess the average electron temperature and mean-square temperature variation (t^2) in the N^+ region as well as the N^+/O^+ ratio. When we require that the empirically-determined values be equal for $(N^+/O^+)_{uv}$ (obtained from the [O II] 2471 and N II] 2142 lines) and $(N^+/O^+)_{opt}$ (obtained from the [O II] 3728 and [N II] 6585 lines), we obtain the following. For the (N^+, O^+)-zone, the average electron density is ~7000 cm^{-3}, the average electron temperature is 9500 K, t^2 is 0.032, and N^+/O^+ is 0.14. In order to obtain N/O, the empirically-derived N^+/O^+ value requires a correction for the possibility that the N^+ and O^+ regions are not identical.

Key words: **H II REGIONS — ISM: ABUNDANCES — ISM: INDIVIDUAL OBJECTS (ORION NEBULA)**

1. INTRODUCTION

Although quantitative nebular spectroscopy is a mature field, several fundamental problems and uncertainties have recently emerged (e.g., Liu et al. 1995). First and foremost are the consequences of changes

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[2]NASA/Ames Research Center, Moffett Field, CA 94035-1000, USA; rubin@cygnus.arc.nasa.gov.

[3]Orion Enterprises.

[4]Rice University, Space Physics & Astronomy, Box 1892, Houston, TX 77251-1892, USA.

[5]University of Kentucky, Physics & Astronomy, Lexington, KY 40506, USA.

[6]Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON, Canada M5S 3H8.

[7]Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile.

[8]Arizona State University, Physics & Astronomy, Tempe, AZ 85287, USA.

[9]South Carolina State University, Physical Sciences, Box 7296, Orangeburg, SC 29117, USA.

in electron temperature (T_e) resulting in mean-square temperature fluctuations (t^2) in nebulae (Peimbert 1967). A modest t^2 can have a major impact on estimates of heavy element abundances. For comprehensive reviews regarding H II regions, see e.g., Peimbert (1993) and Mathis (1995). Observations of Orion (Peimbert, Storey, & Torres-Peimbert 1993) and the PN NGC 7009 (Liu et al. 1995) allowed careful comparison between abundances measured from faint recombination lines and from the classical forbidden lines. These imply that t^2 is large and has caused the abundances of C, N, and O to be underestimated by factors of 2 to 5. The existence of large t^2 is a key question in nebular astrophysics today.

We address the issue of T_e fluctuations as well as the N^+/O^+ ratio in the Orion Nebula using *HST* observations. Much of this work is made possible by our measurements of the N II] lines at λ_{vac} = 2143.45, 2139.68 Å – in sum referred to as 2142 Å.[10] The measurement of this line in Orion is the first in an H II region. Previously it has been seen in RR Tel (Penston et al. 1983), nova CrA 1981 (Williams et al. 1985), the η Car S condensation (Davidson et al. 1986), and planetary nebulae (Vassiliadis et al. 1996). The red component is expected to be a factor of 2.31 stronger than the blue one.

2. *HST* DATA

From our earlier Cycle 3 FOS data, the feature at 2142 Å was identified as emission from the blended pair of N II] lines. Subsequently, we were granted FOS Cycle 5 time for, among other things, further study of the 2143.45, 2139.68 Å lines. In an attempt to maximize the strength of these N II] lines, we utilized the WFPC2 imagery of Orion (from C.R. O'Dell's observations), primarily those taken with F658N. Consequently, we defined FOS-1SW, a circular aperture of 0.86″ diameter, as a Cycle 5 FOS target. Its center is at α, δ = $05^h35^m14\overset{s}{.}71$, $-05°23'41\overset{''}{.}5$) (equinox J2000), 18.5″ S and 26.2″ W of θ^1 Ori C (see Figure 1 in Rubin et al. 1997).

We observed with FOS on 23–24 October, 1995 (UT) using the 0.86″ diameter circular aperture. Spectra were taken with gratings G190H, G270H, G400H, G570H, and G780H, which provide total coverage from about 1650 – 7800 Å. Details of these observations, as well as measured fluxes and pertinent emission line spectra, are reported elsewhere (Rubin et al. 1998, hereafter R98). Most important for this paper is the fact that our observations included in addition to the N II] 2142 lines, [N II] 5756 and 6585; and [O II] 2471 and 3728 – all measured at the same location with *HST*/FOS. We corrected all fluxes for extinction based on our observed FOS data for Balmer, He I, and [O II] emission lines at this position FOS-1SW. This set of corrections is consistent with the shape of the extinction curve derived from observations of the Orion Trapezium stars (Martin et al. 1998).

3. EMPIRICAL ANALYSIS

The acquisition of these lines with the same aperture permits us to address T_e and t^2 along the specific column through the N^+ region. With this information, we can also derive the N^+/O^+ ratio by more than one method. In this paper, we utilize atomic data —electron impact collision strengths and spontaneous emission probabilities (Einstein A-values)— to solve the N^+ energy level populations. We refer to the levels in ascending order of energy; for N^+, these are levels 1–6, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^1S_0$, and $^5S_2$. Effective collision strengths are those of Stafford et al. (1994) at 10000 K; these do not vary much with the T_e range of interest in Orion. There is another contemporaneous calculation by Lennon & Burke (1994) that has somewhat different values. We chose to use the Stafford et al. results because they claim to have included more terms. Effective collision strengths for O^+ (needed as well later) are taken from McLaughlin & Bell (1993) for 10,000 K. These also vary little with T_e within the range of interest here. For other pertinent details, see R98. The A-values for both N^+ and O^+ are from Wiese, Fuhr, & Deters (1996). The only exception is that we use updated recommended values for N^+ A(6–2) = 54.4 s^{-1} and A(6–3) = 125.8 s^{-1} (Jeff Fuhr 1997, private communication).

3.1. Electron Temperature and Mean-Square T_e Variations (t^2)

The observations of lines that arise from levels 4, 5, and 6 of N^+ permit us to address both T_e and t^2 in this region. We treat the combined emission (2142 Å) from level 6; the 5756 Å line from level 5; and the 6585 Å line from level 4. Although our measurements include the 6550 Å line (arising from level 4), we do not use it

[10] All wavelengths used in this paper are on the vacuum scale.

in this analysis because it is weaker than 6585 and closer in wavelength to Hα at 6565 Å than is the 6585 line, causing much more uncertainty in its FOS flux measurement.

Following Peimbert (1967), we may write the flux ratios in a set of equations that utilize a Taylor series expansion about an average electron temperature T_X defined by

$$T_X = \frac{\int T_e N_e N(N^+) dV}{\int N_e N(N^+) dV} , \qquad (1)$$

and retain terms to second order. These involve terms containing t_X^2, the mean-square temperature variation, defined by the following equation,

$$t_X^2 = \frac{\int (T_e - T_X)^2 N_e N(N^+) dV}{T_X^2 \int N_e N(N^+) dV} . \qquad (2)$$

The integration in equations (1) and (2) is over the column defined by the aperture, along the line-of-sight. Then for the 2142 to 5756 flux ratio,

$$\frac{F_{2142}}{F_{5756}} = \frac{K_6}{K_5} \exp\left(-\frac{20284}{T_X}\right) C_{tvar}. \qquad (3)$$

In the above equation, $(K_6/K_5)\exp(-20284/T_X) = \epsilon_{2142}/\epsilon_{5756}$, where ϵ_λ is the normalized volume emissivity, written in terms of the volume emissivity for the line $\jmath_\lambda$ as $\epsilon_\lambda \equiv \jmath_\lambda/(N_e N_i)$. N_i is the relevant ion density. ϵ_λ depends on the level populations only. It is helpful to "factor out" the differential Boltzmann factor dependence.

We follow the technique in Peimbert (1967), Rubin (1969), and notation of Rubin et al. (1988) to write the correction factor for T_e-variations (C_{tvar}) as

$$C_{tvar} = \frac{1 + b_{\lambda 1} t_X^2}{1 + b_{\lambda_2} t_X^2} , \qquad (4)$$

where subscripts $\lambda 1$ and $\lambda 2$ refer to the respective b–values for the pertinent lines and

$$b_\lambda = \frac{1}{2} \left[(\chi/k\, T_X)^2 - 3(\chi/k\, T_X) + 3/4\right] . \qquad (5)$$

χ is the excitation energy above ground for the upper level of the transition. Similarly, forming the other flux ratios, we arrive at equations (6) and (7).

$$\frac{F_{5756}}{F_{6585}} = \frac{K_5}{K_4} \exp\left(-\frac{24993}{T_X}\right) C_{tvar}; \qquad (6)$$

$$\frac{F_{2142}}{F_{6585}} = \frac{K_6}{K_4} \exp\left(-\frac{45277}{T_X}\right) C_{tvar}. \qquad (7)$$

The evaluation of T_X from equations (3), (6), and (7) is done by solving the statistical equilibrium for the 6-level populations.

3.2. N^+/O^+ Ratio

We proceed with an empirical method to infer the N^+/O^+ ratio from the *HST* Orion data. We refer to the value obtained for N^+/O^+ from the "traditional" method that uses line fluxes from 6585 and 3728 Å as $(N^+/O^+)_{opt}$. T_X and t_X^2 can be different for the O^+ region and the N^+ region (X was used to denote the possibility of different ions). $N(O^+)$ would replace $N(N^+)$ in equations (1) and (2). While detailed photoionization models can produce theoretical values for T_X and t_X^2 in both $N(O^+)$ and $N(N^+)$, among others, with the empirical analysis there is no means to distinguish possible different values. Hence, we assume that T_X and t_X^2 found for N^+ apply for both zones. Unless the ionization structure were the same for both, this assumption may not be correct.

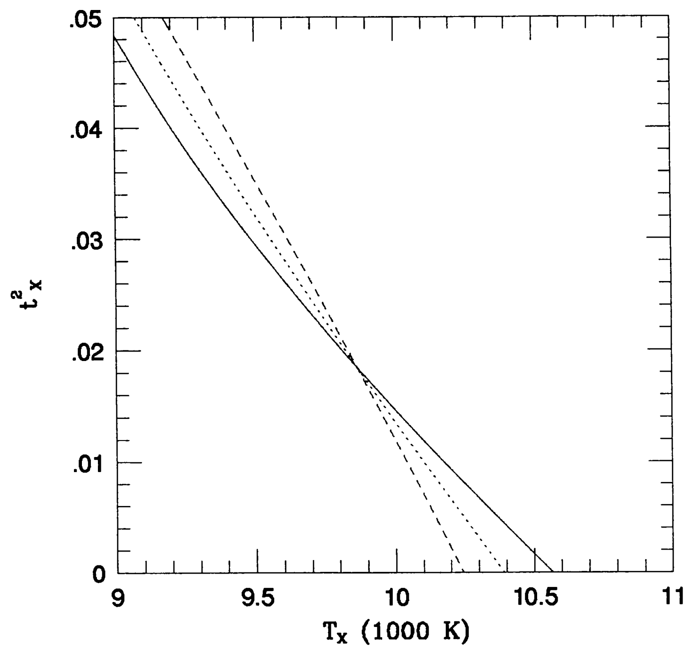

Fig. 1. Loci of solutions for each of equations (3), (6), and (7) (solid, heavy-dashed, and small-dashed lines, respectively). We use the Orion Nebula extinction-corrected flux ratios (see R98) and $N_e = 6000$ cm^{-3}. Where these lines cross the x-axis is the T_e value that would be inferred for each equation in the absence of T_e fluctuations. The intersection of the loci at $T_X = 9862$ K, $t_X^2 = 0.01849$ is the desired solution for this value of the density.

To find an expression for $(N^+/O^+)_{opt}$, we proceed as above, by "factoring out" the differential Boltzmann factor dependence and writing

$$(\mathrm{N}^+/\mathrm{O}^+)_{\mathrm{opt}} = \frac{K'_{23}}{K_4} \exp\left(-\frac{16548}{T_X}\right) \frac{\mathrm{F}_{6585}}{\mathrm{F}_{3728}} \frac{1 + \mathrm{b}_{3728}\, \mathrm{t}_X^2}{1 + \mathrm{b}_{6585}\, \mathrm{t}_X^2} \ . \tag{8}$$

In this equation, (K'_{23}/K_4) exp $(-16548/T_X) = (\epsilon_{3727} + \epsilon_{3730})/\epsilon_{6585}$; K_4 refers to level 4 of N^+ as before, and K'_{23} refers to levels 2 and 3 of O^+. The analogous equation for $(N^+/O^+)_{uv}$ using N II] 2142 and [O II] 2471 is:

$$(\mathrm{N}^+/\mathrm{O}^+)_{\mathrm{uv}} = \frac{K'_{45}}{K_6} \exp\left(+\frac{9089}{T_X}\right) \frac{\mathrm{F}_{2142}}{\mathrm{F}_{2471}} \frac{1 + \mathrm{b}_{2471}\, \mathrm{t}_X^2}{1 + \mathrm{b}_{2142}\, \mathrm{t}_X^2} \ . \tag{9}$$

The evaluation of N^+/O^+ is carried out for particular combinations of N_e and T_e by solving the 5 or 6-level atom for the populations, which provide the necessary values of ϵ_λ; a consistent value of t_X^2 is to be used.

3.3. Applications to the HST Orion Nebula Data

Some indication of N_e in the N^+ zone may be obtained from the N_e derived from the [S II] lines 6718 and 6733 Å ($N_e = 10275$ cm^{-3}). Unfortunately, our FOS measurements cannot resolve the individual components of [O II] 3727, 30 (combined referred to as 3728). It would be very useful to have these measurements corresponding to FOS-1SW because the N_e in the O^+ region is likely a much better measure of N_e in the N^+ zone than is the sulfur value. When we attempt to solve equations (3), (6), and (7) with N_e from the [S II] lines using the three N II extinction-corrected flux ratios (R98) there are no solutions. There are in fact no solutions until $N_e \lesssim$ 7100 cm^{-3}. The largest value of N_e that permits a solution for the Orion data is 7000 cm^{-3} (to the nearest 100). The curves representing the loci for equations (3), (6), and (7) intersect at $T_X = 9185$ K, $t_X^2 = 0.04367$ (see R98). When $N_e = 6000$ cm^{-3}, we obtain the solution $T_X = 9862$ K, $t_X^2 = 0.01849$ graphically presented in Figure 1. The x-intercepts of the lines represent T_e that would be derived by ignoring temperature variations

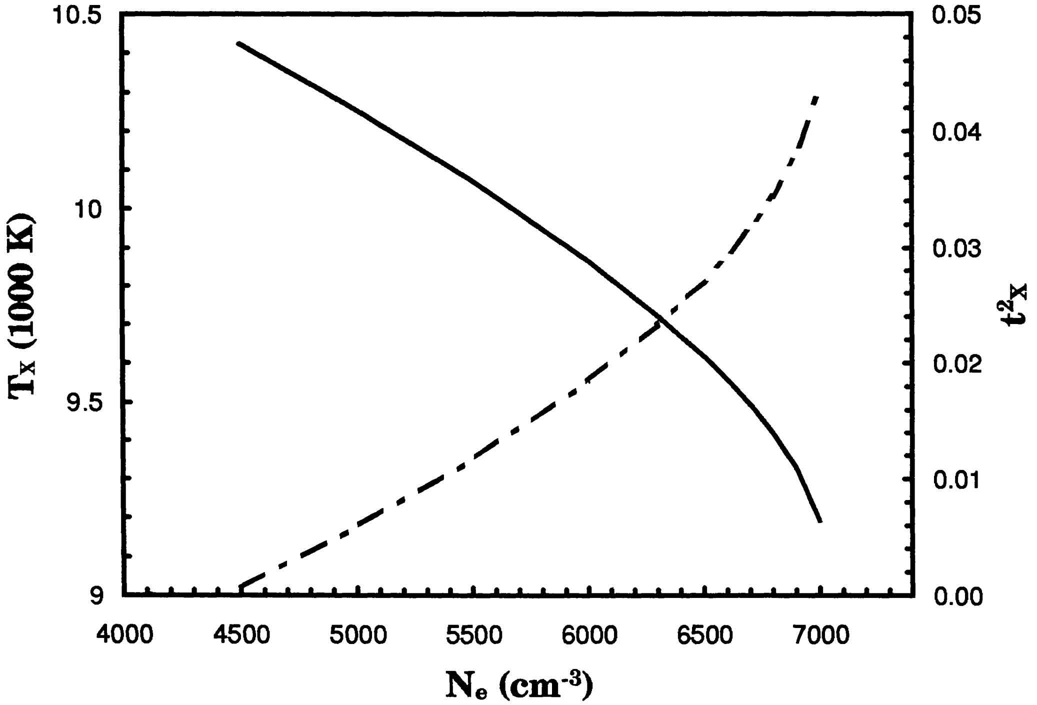

Fig. 2. With the solution for equations (3), (6), and (7) depending on the assumed N_e, we calculate a set of "intersection points" (such as in Fig. 1) for a number of different assumed N_e-values for the Orion (N^+, O^+)-region spanning the range where there are solutions. The solid line is for T_X vs. N_e; the broken line is for t^2_X vs. N_e.

($t^2_X = 0$): T_{65} = 10568 K (subscript denotes energy levels from which lines arise); T_{64} = 10392 K; and T_{54} = 10244 K. There is a second solution that is spurious/non-physical at high t^2_X (not shown). This behavior is discussed in R98 with test models to confirm that this other solution is physically meaningless.

With the solution depending on the assumed N_e, we calculate, where possible, a set of "intersection solutions" for a number of different assumed N_e-values, for the Orion (N^+, O^+)-region. This is shown in Figure 2 taken from R98. With decreasing N_e, the intersection seen in Fig. 1 slides down to lower t^2_X and higher T_X. When we attempt to solve equations (3), (6), and (7) with $N_e \lesssim 4400$ cm^{-3}, then the intercepts $T_{65} < T_{64} < T_{54}$, and there is no physically meaningful solution. (There is again the spurious, non-physical solution at very high t^2_X). Figure 3 shows this situation for $N_e = 3000$ cm^{-3}. Indeed, the intercepts $T_{65} \geq T_{64} \geq T_{54}$, must hold if there is to be a possible, physically meaningful solution.

The reason that there are no solutions here when $N_e \gtrsim 7100$ cm^{-3} is due to omitting higher-order terms than second order in the analysis. By expanding the analysis to fourth-order (R98), we demonstrate this behavior with test cases that are able to explain the lack of solutions at these densities. The lack of solutions when N_e is below some threshold ($\lesssim 4400$ cm^{-3} here) is directly related to the N^+ atomic data adopted, particularly the collision strengths. Changes in the atomic data may influence the region of N_e-parameter space where **both** the low and high density non-solutions occur (R98). Naturally, errors in the measurements or extinction corrections will also contribute to where the onset of **both** the low- and high-N_e-realm of no solutions occurs.

Let us now move on to addressing the N^+/O^+ ratio. We use the extinction-corrected flux ratios to derive $(N^+/O^+)_{opt}$ from equation (8) and $(N^+/O^+)_{uv}$ from equation (9). From our derivation of the shape of the Orion extinction curve (Martin et al. 1997), the effect of differential extinction is larger in the case of the optical determination of N^+/O^+ than is the case for the UV. For FOS-1SW, we find that the observed ratio F_{2142}/F_{2471} must be increased by a factor of 1.32, which is less than for F_{3728}/F_{6585}, which requires a correction factor of 1.70. To solve equations (8) and (9) we use the various values of N_e considered above for the (N^+, O^+) zone and use the corresponding pairs of T_X and t^2_X displayed in Fig. 2. The resulting loci for each determination are shown in Figure 4, reproduced from R98. Fortuitously, the two curves just cross at $N_e \sim 7000$ cm^{-3}, the largest value of N_e that permits a solution for the Orion data.

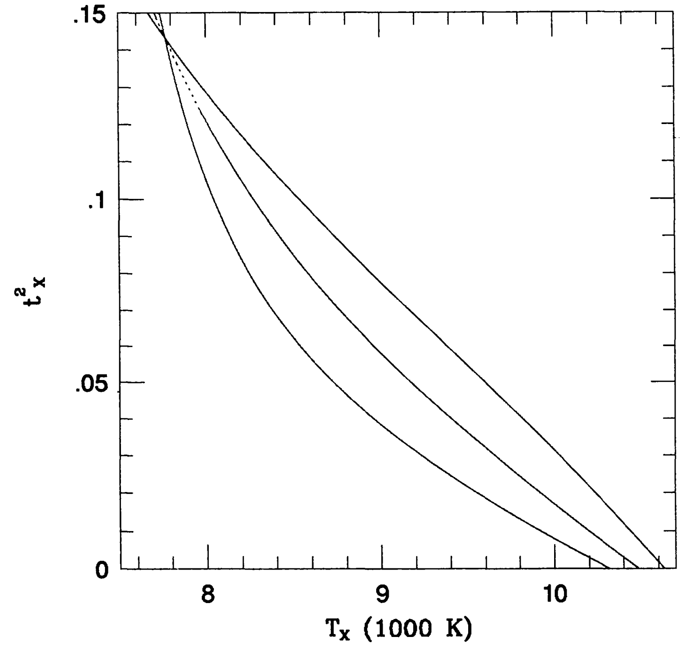

Fig. 3. This is the same as Fig. 1 except that here we use N_e = 3000 cm^{-3}. There is no meaningful solution to the set of equations. There is a spurious solution at T_X = 7770 K and very high t^2_X = 0.143 (see text).

It is reasonable to consider this a "preferred" solution because the two methods should provide similar results. Here, using T_X = 9185 K, t^2_X = 0.0437, $(N^+/O^+)_{opt}$ = 0.1398 and $(N^+/O^+)_{uv}$ = 0.1407. The trend of $(N^+/O^+)_{opt}$ decreasing and $(N^+/O^+)_{uv}$ increasing with increasing $N_e > 7000$ is expected to continue. Thus, where the two determinations are equal is unique and well-defined.

In view of the results encountered with the test cases (R98), we feel that some adjustment is necessary to the (T_X, t^2_X)-solution near the high-N_e end of the curves in Figure 2. As the "transition" value of N_e = 7000 cm^{-3} is approached, both T_X and t^2_X are changing rather dramatically. When N_e changes from 6800 to 7000 cm^{-3}, T_X changes from 9413 to 9185 K and t^2_X from 0.03453 to 0.04367. We may draw on the results of the test cases for guidance. There, we have used N_e = 1 cm^{-3} to insure that all lines are below their respective critical densities in order to validate the procedure using the Taylor series expansion. This assumes the low-density limit functional form for the volume emissivities proportional to $T_e^{-0.5}\exp(-\chi/k\,T_e)$. Then, predominantly as a result of not accounting for t^4_X-terms, the solution of equations (3), (6), and (7) was found to be at a temperature 234 K too low and a t^2_X 0.0089 too high compared with the true values. Indications from further test cases are that at densities close to the values found here from our Orion data, the necessary adjustment will be even larger. Using a test case that has been fine-tuned to match the Orion results, we find a T_X that is 337 K too small & a t^2_X that is 0.01217 too large compared with the true values. We apply these differences to the Orion "solution" at N_e = 7000 to arrive at the preferred values T_X = 9522 K and t^2_X = 0.0315. Our conclusion that N^+/O^+ = 0.14 remains unaltered even after considering the effects of this adjustment (see R98).

It is important to realize that in general $N/O \neq N^+/O^+$ and that it is necessary to apply ionization correction factors (*icfs*). Unless the ionization structure of N^+ and O^+ were the same, this is necessary. This is discussed in R98, where detailed photoionization models of Orion are also considered.

4. SUMMARY, DISCUSSION, AND CONCLUSIONS

We highlight and discuss the main points of the paper.

• *HST* measurement of the N II] 2140, 2143 Å lines in the Orion Nebula permits several new astrophysical applications. In conjunction with *HST* line measurements of [N II] 5756 and 6585 Å in the same

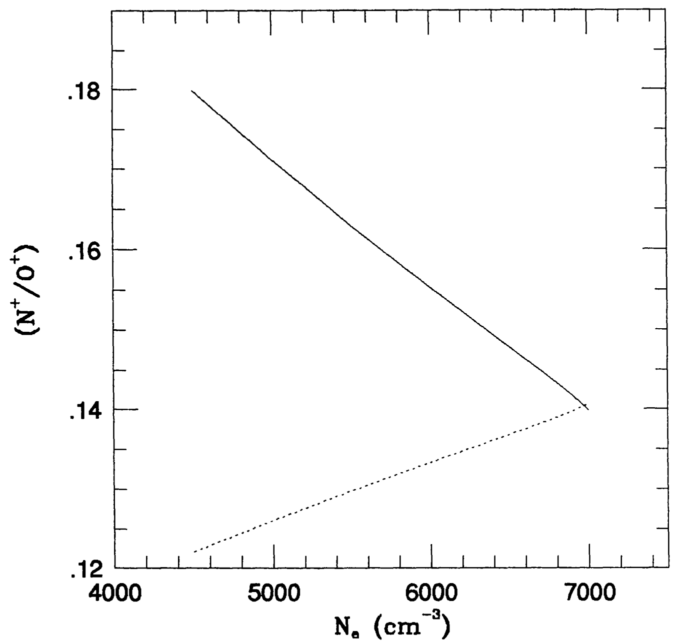

Fig. 4. The resulting loci for the determination of $(N^+/O^+)_{opt}$ (solid line) and $(N^+/O^+)_{uv}$ (dashed line) vs. N_e when we use the set of solutions shown in Figure 2. The two curves intersect at a point, which we consider our "preferred" solution $N^+/O^+ = 0.14$, because the two methods should provide similar results.

aperture/location, we are able with an empirical method to address the average electron temperature and t^2 in the particular observed N^+ volume.

• When we utilize the fluxes of the nitrogen lines above with our cospatial measurements of the [O II] 2471 Å and 3728 Å lines, we are able to derive the N^+/O^+ ratio empirically two ways. We determine $(N^+/O^+)_{uv}$ from the N II]2142/[O II]2471 ratio and $(N^+/O^+)_{opt}$ from the well-known [N II]6585/[O II]3728 ratio. Each of these abundance ratios is formulated in terms of the average T_e and t^2. Our preferred empirical solution is obtained by requiring that $(N^+/O^+)_{opt}$ and $(N^+/O^+)_{uv}$ be equal. This yields for the (N^+, O^+)-zone, an average electron density ~7000 cm^{-3}, an average $T_e = 9500$ K, $t^2 = 0.032$, and $N^+/O^+ = 0.14$. The reliability of the empirical analysis for N^+/O^+ is dependent on how closely the N^+ and O^+ volumes coincide in order that the average T_e and t^2 for the N^+ region also be valid for the O^+ region.

• If $t^2_X \gtrsim 0.04$, then the method to derive T_X and t^2_X from the N^+ lines may start to suffer from the omission of higher-order T_e-variation terms. This could be manifested by an inability to find a solution to the set of N^+ flux ratio equations. Even if there is a solution that finds such a high t^2_X, one needs to be cognizant of the possibility that the solution is somewhat in error because of the omission in the analysis of higher-order terms that are no longer negligible.

• Our plans for Cycle 7 with the Space Telescope Imaging Spectrograph (STIS) include a slit spectrum through position 1SW. This should resolve individually [O II] 3727, 3730 Å providing needed N_e information. We speculate that the current rather large value derived for t^2 may be the result of the narrow FOS solid angle (represented by a cylinder cutting through the nebula) experiencing relatively more local "meteorology" (small-scale structure). One might wonder if t^2 inferred for a larger volume would be smaller. Our Cycle 7 long-slit STIS observations should be able to test this. Nevertheless, values of t^2 as large as 0.032 remain a challenge for "standard" photoionization models to explain. We plan to pursue an improved theoretical model for Orion. We also plan further investigation of the empirical methods presented. These include studies of the effects of density variations and using other atomic data, such as substituting the Lennon & Burke (1994) N^+ effective collision strengths.

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REFERENCES

Davidson, K., Dufour, R. J., Walborn, N. R., & Gull, T. R. 1986, ApJ, 305, 867

Lennon, D. J. & Burke, V. M. 1994, A&AS, 103, 273

Liu, X., Storey, P. J., Barlow, M. J., & Clegg, R. E. S. 1995, MNRAS, 272, 369

Martin, P. G., et al. 1998, in preparation

Mathis, J. S. 1995, in The Fifth Mexico-Texas Conference on Astrophysics: Gaseous Nebulae and Star Formation, ed. M. Peña & S. Kurtz, RevMexAASC, 3, 207

McLaughlin, B. M., & Bell, K. L. 1993, ApJ, 408, 753

Peimbert, M. 1967, ApJ, 150, 825

____________. 1993, RevMexAA, 27, 9

Peimbert, M., Storey, P. J., & Torres-Peimbert, S. 1993, ApJ, 414, 626

Penston, M. V., et al. 1983, MNRAS, 202, 833

Rubin, R. H. 1969, ApJ, 155, 841

Rubin, R. H., Simpson, J. P., Erickson, E. F., & Haas, M. R. 1988, ApJ, 327, 377

Rubin, R. H., Dufour, R. J., Ferland, G. J., Martin, P. G., O'Dell, C. R., Baldwin, J. A., Hester, J. J., & Walter, D. K. 1998, ApJ, submitted (R98)

Rubin, R. H., Dufour, R. J., Ferland, G. J., Martin, P. G., O'Dell, C. R., Baldwin, J. A., Hester, J. J., Walter, D. K., & Wen, Z. 1997, ApJ, 474, L131

Stafford, R. P., Bell, K. L., Hibbert, A., & Wijesundera, W. P. 1994, MNRAS, 268, 816

Vassiliadis, E., Dopita, M. A., Bohlin, R. C., Harrington, J. P., Ford, H. C., Meatheringham, S. J., Wood, P. R., Stecher, T. P., & Maran, S. P. 1996, ApJS, 105, 375

Wiese, W. L., Fuhr, J. R., & Deters, T. M. 1996, NIST Monograph #7, J.Phys.Chem.Ref.Data

Williams, R. E., Ney, E. P., Sparks, W. M., Starrfield, S. G., Wyckoff, S., & Truran, J. W. 1985, MNRAS, 212, 753