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TEMPERATURE VARIATIONS AND N^+/O^+ IN THE ORION NEBULA II. THE COLLISION STRENGTHS[1]

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RESUMEN

Continuamos una investigación de la temperatura electrónica (T_e), la variación rms de T_e, (t^2), y el cociente de abundancias N^+/O^+. En nuestros análisis anteriores de espectros de HST de la nebulosa de Orión se usaron fuerzas de colisión para N^+ calculadas por Stafford et al.(1994). Aquí examinamos el efecto de sustituir estos valores por los de Lennon & Burke (1994). En lugar de utilizar la aproximación de baja densidad N_e, presentamos una técnica numérica que es válida para cualquier densidad. Con las fuerzas de colisión de Stafford et al. encontramos que la densidad N_e promedio para la región (N^+, O^+) es 7500 cm^{-3}, la temperatura promedio es 9160 K, t^2 es 0.045 y N^+/O^+ es 0.14. Usando los valores de Lennon & Burke, la "mejor" solución se encuentra cuando las mismas variables tienen los valores 9000 cm^{-3}, 9920 K, 0.00073, y 0.15, respectivamente. El valor de t^2 es mucho menor que el que se encuentra usando los datos de Stafford et al.

ABSTRACT

We continue an investigation of electron temperature (T_e), mean–square T_e variation (t^2), and the N^+/O^+ abundance ratio. Our previous analysis of HST spectra of the Orion Nebula used collision strengths for N^+ by Stafford et al. (1994). Here we examine the consequences of changing *just* these collision strengths by using those of Lennon & Burke (1994). Rather than utilize the standard analytical, low electron density (N_e) regime treatment for the analysis, we develop a numerical technique that is valid at any density. With Stafford et al. collision strengths, we find the average N_e for the (N^+, O^+)–zone is 7500 cm^{-3}, the average T_e is 9160 K, t^2 is 0.045, and N^+/O^+ is 0.14. Using Lennon & Burke values, the "best" solution is found when these respective quantities are: 9000 cm^{-3}, 9920 K, 0.00073, and 0.15. The value for t^2 is dramatically lower than that found using Stafford et al. data.

Key Words: **ISM: ABUNDANCES — ISM: H II REGIONS — ISM: INDIVIDUAL: ORION NEBULA**

1. INTRODUCTION

Most observational tests of the chemical evolution of the universe rest on emission line objects; these define the endpoints of stellar evolution and probe the current state of the interstellar medium. H II regions and Planetary Nebulae (PNs) are laboratories for understanding physical processes in all emission–line sources, and probes for stellar, galactic, and primordial nucleosynthesis. There is mounting evidence of a very fundamental

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problem – heavy element abundances inferred from emission lines that are collisionally excited are generally significantly smaller than those derived from lines due to recombination/cascading ("recombination lines"). We refer to this as "the abundance dichotomy". Studies of PNs contrasting recombination and collisional abundances (e.g., Liu et al. 1995; Kwitter & Henry 1998) often find differences exceeding a factor of two. An extensive recent study of the PN NGC 6153 found that C^{++}/H^{+}, N^{++}/H^{+}, O^{++}/H^{+}, and Ne^{++}/H^{+} ratios derived from optical recombination lines are all a factor of $\sim$10 higher than the corresponding values deduced from collisionally–excited lines (Liu et al. 2000). Most of the efforts to explain the abundance dichotomy have attempted to do so by examining electron temperature (T_e) variations in the plasma. This is often done, using the formalism of Peimbert (1967), in terms of the mean–square T_e variation (t^2). In previous work, we addressed the issue of t^2 as well as the N^+/O^+ ratio in the Orion Nebula using *HST* observations (Rubin et al. 1998a, R98; Rubin et al. 1998b). Much of this work was 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 (vacuum λs are used in this paper). Previously we used collision strengths for N^+ by Stafford et al. (1994). Here we extend our earlier study, again using the *HST* data in R98, and also repeat the analysis changing <u>only</u> N^+ collision strengths to those of Lennon & Burke (1994). This paper is an encapsulation of a more detailed paper in preparation (Rubin et al. 2001).

2. ELECTRON TEMPERATURE AND MEAN–SQUARE VARIATIONS FROM LINES OF N^+

We assume that the lines are collisionally excited with negligible contribution from recombination. This is expected for the Orion Nebula from detailed models (Baldwin et al. 1991; Rubin et al. 1991). The observed line flux F_λ (e.g., in W cm^{-2}) is given by

$$\mathrm{F}_\lambda \;=\; \frac{1}{4\pi \mathrm{D}^2} \int \epsilon_\lambda \, N_e \, N_i \, dV \quad , \tag{1}$$

where D is the distance. We are interested in the normalized volume emissivity of a line, ϵ_λ, which is related to the usual volume emissivity $\jmath_\lambda$ by $\epsilon_\lambda \equiv \jmath_\lambda/(N_e N_i)$. N_i is the relevant ion density; ϵ_λ depends on the (fractional) population in a given level, which depends on T_e and N_e. We follow the technique in Peimbert (1967) and Rubin (1969), using the notation of R98, making a Taylor series expansion of ϵ_λ about an average electron temperature $\mathrm{T_X}$ defined by

$$\mathrm{T_X} \;=\; \frac{\int \mathrm{T_e\, N_e\, N(N^+)\, dV}}{\int \mathrm{N_e\, N(N^+)\, dV}} \quad . \tag{2}$$

The integration in equation (2) is over the column defined by the aperture, along the line–of–sight. Following earlier work, we may cast the correction in terms of the Taylor expansion by using a correction factor (cf):

$$(cf)_\lambda = 1 + \mathrm{b}_\lambda \mathrm{t_X^2} + \mathrm{c}_\lambda \mathrm{t_X^3} + \mathrm{d}_\lambda \mathrm{t_X^4} + \ldots \quad , \tag{3}$$

where

$$\mathrm{b}_\lambda \;=\; \frac{\mathrm{T_X^2}}{2!\epsilon}\,\frac{\mathrm{d}^2\epsilon}{\mathrm{dT}^2} \;;\quad \mathrm{c}_\lambda \;=\; \frac{\mathrm{T_X^3}}{3!\epsilon}\,\frac{\mathrm{d}^3\epsilon}{\mathrm{dT}^3} \;;\quad \mathrm{d}_\lambda \;=\; \frac{\mathrm{T_X^4}}{4!\epsilon}\,\frac{\mathrm{d}^4\epsilon}{\mathrm{dT}^4} \;, \tag{4}$$

and

$$\mathrm{t_X^n} \;=\; \frac{\int \mathrm{(T_e - T_X)^n\, N_e\, N(N^+)\, dV}}{\mathrm{T_X^n} \int \mathrm{N_e\, N(N^+)\, dV}} \quad . \tag{5}$$

For conciseness, the λ subscript on ϵ is omitted.

A numerical treatment may handle any function for ϵ and thus the important general case of forbidden line emission at any density, not just the low–N_e limit. The previous restriction may be circumvented by replacing the analytical treatment with a numerical one using finite differences. The central differences representation for the above derivatives replaces them with differences (e.g., $\mathrm{d}^2\epsilon/\mathrm{dT}^2$ with δ_n^2), where

$$\delta_n^2 = \epsilon_{n+1} - 2\epsilon_n + \epsilon_{n-1}, \tag{6}$$

$$\delta_n^3 = \epsilon_{n+3/2} - 3\epsilon_{n+1/2} + 3\epsilon_{n-1/2} - \epsilon_{n-3/2} = (\epsilon_{n+3} - 3\epsilon_{n+1} + 3\epsilon_{n-1} - \epsilon_{n-3})/8, \tag{7}$$

$$\delta_n^4 = \epsilon_{n+2} - 4\epsilon_{n+1} + 6\epsilon_n - 4\epsilon_{n-1} + \epsilon_{n-2}, \tag{8}$$

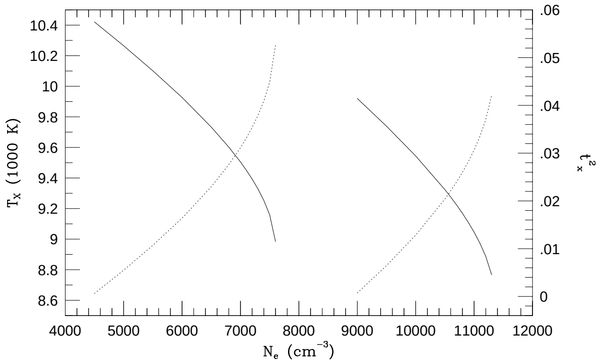

Fig. 1. The resulting loci for T_X (solid line) and t_X^2 (dashed line) vs. N_e when we use the set of solutions obtained from equations 10 with the *HST* data in R98. The two curves on the left result from using Stafford et al. collision strengths; $N_e = 7600$ cm^{-3} is the highest density with a solution. The two curves on the right result from using Lennon & Burke collision strengths. $N_e = 9000$ cm^{-3} is the lowest N_e with a solution.

$$\mathrm{b}_\lambda = \frac{\mathrm{T}_\mathrm{n}^2}{2!\epsilon_\mathrm{n}}\,\delta_n^2\ ;\quad \mathrm{c}_\lambda = \frac{\mathrm{T}_\mathrm{n}^3}{3!\epsilon_\mathrm{n}}\,\delta_n^3\ ;\quad \mathrm{d}_\lambda = \frac{\mathrm{T}_\mathrm{n}^4}{4!\epsilon_\mathrm{n}}\,\delta_n^4\ . \tag{9}$$

Subscript n represents the central point with temperature T_n. We compute these differences using a $\Delta\mathrm{T} = 1$ K; subscript $n+1$ represents the point with temperature T_n+1, and so forth. We may now write three equations for the N$^+$ line flux ratios that are the generalized equivalent of equation (3), (6), and (7) in R98.

$$\frac{F_{2142}}{F_{5756}} = \frac{\epsilon_{2142}}{\epsilon_{5756}}\frac{(cf)_{2142}}{(cf)_{5756}}\ ;\qquad \frac{F_{5756}}{F_{6585}} = \frac{\epsilon_{5756}}{\epsilon_{6585}}\frac{(cf)_{5756}}{(cf)_{6585}}\ ;\qquad \frac{F_{2142}}{F_{6585}} = \frac{\epsilon_{2142}}{\epsilon_{6585}}\frac{(cf)_{2142}}{(cf)_{6585}}. \tag{10}$$

If we now assume that t^2 values are not large and do the usual restriction to the above expressions by neglecting terms higher than second order (i.e., maintain just the first two terms in equation 3), equations (10) provide the loci of possible solutions in the (T_X, t_X^2)–plane for a given N_e. As discussed in R98, there may or may not be a common solution for these equations. When there is a solution, all three loci will intersect at a point. The set of possible solutions is shown in Figure 1.

3. N$^+$/O$^+$ RATIO

We continue with our empirical method analysis to infer N$^+$/O$^+$ values from the *HST* data (see R98). We refer to the value obtained for N$^+$/O$^+$ from the "traditional" method that uses line fluxes from 6585 and 3728 Å (3727,30) as $(\mathrm{N}^+/\mathrm{O}^+)_{opt}$. The evaluation of $(\mathrm{N}^+/\mathrm{O}^+)_\mathrm{opt}$ with the appropriate $(cf)_\lambda$ factors (to second order) from equation (3) for the two lines used is accomplished by solving the five– or six–level atom for the populations apropos to the N_e, T_e values. This provides the necessary values for ϵ_λ. Similar to previous expressions,

$$(\mathrm{N}^+/\mathrm{O}^+)_\mathrm{opt} = \frac{F_{6585}}{F_{3728}}\,\frac{(\epsilon_{3727} + \epsilon_{3730})}{\epsilon_{6585}}\,\frac{(cf)_{3728}}{(cf)_{6585}}. \tag{11}$$

The analogous relation for $(\mathrm{N}^+/\mathrm{O}^+)_\mathrm{uv}$ using N II] 2142 and [O II] 2471 Å is

$$(\mathrm{N}^+/\mathrm{O}^+)_\mathrm{uv} = \frac{\mathrm{F}_{2142}}{\mathrm{F}_{2471}}\,\frac{\epsilon_{2471}}{\epsilon_{2142}}\,\frac{(cf)_{2471}}{(cf)_{2142}}. \tag{12}$$

As previously, we have assumed that **1)** T_X and t_X^2 found for the N$^+$ zone apply for the O$^+$ zone as well, and **2)** N_e applies for both the N$^+$ and O$^+$ regions. The set of possible solutions, with our *HST* data in R98, is shown in Figure 2.

4. SUMMARY, DISCUSSION AND CONCLUSIONS

• We examine the consequences of changing only the set of N$^+$ collision strengths using an empirical analysis based on our earlier cospatial *HST* measurement of the Orion Nebula, including N$^+$ lines 2142, 5756, and 6585 Å and O$^+$ lines 2471 and 3728 Å. These data allow us to derive the average T_e and t^2 in the particular observed N$^+$ volume and to derive the N$^+$/O$^+$ ratio two ways. We determine $(\mathrm{N}^+/\mathrm{O}^+)_{uv}$ from the N II] 2142/[O II]

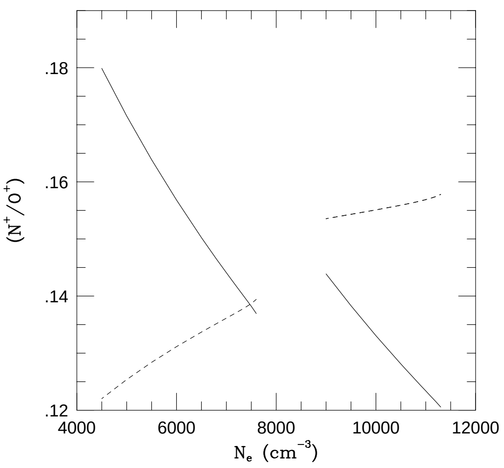

Fig. 2. The resulting loci for the determination of $(\mathrm{N}^+/\mathrm{O}^+)_{opt}$ (solid line) and $(\mathrm{N}^+/\mathrm{O}^+)_{uv}$ (dashed line) vs. N_e when we use the set of solutions obtained from equations 10 in equations 11 and 12. The two curves on the left result from using Stafford et al. collision strengths and intersect at a point, which we consider our "preferred" solution $\mathrm{N}^+/\mathrm{O}^+ = 0.14$, because the two methods should provide similar results. The two curves on the right result from using Lennon & Burke collision strengths. $N_e = 9000$ cm^{-3} is the lowest N_e with a solution and is our "preferred" solution yielding $\mathrm{N}^+/\mathrm{O}^+ \sim 0.15$.

2471 ratio and $(\mathrm{N}^+/\mathrm{O}^+)_{opt}$ from the [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 $(\mathrm{N}^+/\mathrm{O}^+)_{opt}$ and $(\mathrm{N}^+/\mathrm{O}^+)_{uv}$ be equal.

• We repeat our prior analysis using Stafford et al. (1994) collision strengths. The results here are somewhat changed from our earlier ones (R98) because of the improved numerical treatment described herein. We find for the (N^+, O^+)–zone, an average $N_e = 7500$ cm^{-3}, an average $T_e = 9160$ K, $t^2 = 0.045$, and $\mathrm{N}^+/\mathrm{O}^+ = 0.14$. We then substitute the Lennon & Burke N^+ collision strengths for those of Stafford et al. and redo the analysis. Then our "best" solution is found when $(\mathrm{N}^+/\mathrm{O}^+)_{opt} \sim (\mathrm{N}^+/\mathrm{O}^+)_{uv}$. The respective quantities are: 9000 cm^{-3}, 9920 K, 0.00073, and 0.15.

• The value for t^2 is dramatically lower than that found using Stafford et al. data. Values of t^2 as large as 0.045 remain a challenge for "standard" photoionization models to explain. In this regard, the Lennon & Burke solution is more palatable. Interestingly, the inferred $\mathrm{N}^+/\mathrm{O}^+$ is little changed.

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