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TEMPERATURE VARIATIONS FROM *HST* SPECTROSCOPY OF NGC 1976[1]

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RESUMEN

Presentamos espectroscopía de rendija larga con *HST*/STIS para NGC 1976. Medimos el cociente de flujo intrínseco entre las líneas [O III] 4364/5008 para evaluar la temperatura electrónica (T_e) y variación fraccional media cuadrada de T_e (t_A^2) *en toda la nebulosa*. También medimos el cociente de flujo intrínseco entre [N II] 5756/6585 para estimar T_e y t_A^2 en la región N^+. La interpretación de los datos de [N II] no es tan clara como lo es para los datos de [O III] debido a la dependencia de la densidad electrónica (N_e). Presentamos resultados de agregar los datos a lo largo de las diversas rendijas en regiones de 0.5″ por lado. La temperatura promedia del [O III] para las cuatro rendijas de *HST*/STIS varía entre 7678 K y 8358 K; t_A^2 varía de 0.00682 a 0.0176. Cuando usamos N_e de 8000 (para las rendijas 1 y 2) y 3000 cm^{-3} (para las rendijas 4 y 5) con intensidades colisionales de Lennon & Burke (1994), la temperatura promedio para [N II] para cada una de las cuatro rendijas varía de 8979 K a 9761 K; t_A^2 varía de 0.00551 a 0.0172. Las mediciones de T_e que se reportan son promediadas a lo largo de la línea de visión. Por lo tanto, a pesar de encontrar valores de t_A^2 muy bajos, no podemos descartar fluctuaciones en temperatura significativamente mas altas a lo largo de la línea de visión. Nuestros resultados sobre la T_e promedio de [N II] y la de [O III] confirma lo que se ha encontrado anteriormente en Orión y lo que se espera en base a la teoría.

ABSTRACT

We present *HST*/STIS long-slit spectroscopy of NGC 1976. Our goal is to measure the intrinsic line flux ratio [O III] 4364/5008 and thereby evaluate the electron temperature (T_e) and the fractional mean-square T_e variation (t_A^2) *across the nebula*. We also measure the intrinsic line flux ratio [N II] 5756/6585 in order to estimate T_e and t_A^2 in the N^+ region. The interpretation of the [N II] data is not as clear cut as the [O III] data because of a higher sensitivity to knowledge of the electron density (N_e). We present results from binning the data along the various slits into tiles that are 0.5″ square. The average [O III] temperature for our four *HST*/STIS slits varies from 7678 K to 8358 K; t_A^2 varies from 0.00682 to 0.0176. When we use N_e of 8000 (for slits 1 and 2) and 3000 cm^{-3} (for slits 4 and 5) with Lennon & Burke (1994) collision strengths, the average [N II] temperature for each of the four slits varies from 8979 K to 9761 K; t_A^2 varies from 0.00551 to 0.0172. The measurements of T_e reported here are an average along each line of sight. Therefore, despite finding remarkably low t_A^2, we cannot rule out significantly larger temperature fluctuations along the line of sight. The result that the average [N II] T_e exceeds the average [O III] T_e confirms what has been previously found for Orion and what is expected on theoretical grounds.

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

1. INTRODUCTION

This paper includes a synopsis of a more detailed, recent study of Orion Nebula *HST* data and analyses (Rubin et al. 2003 = R03). That paper, as well as this one, are extensions of an earlier paper (Rubin et al. 2002 = Paper I) that used *HST* STIS and WFPC2 observations to study the variation of T_e in NGC 7009 as determined from the [O III] (4364/5008) flux ratio. Very low values for variations in the plane of the sky (t_A^2) were found (always $\lesssim$0.01). In this paper, we focus solely on T_e variations with the purpose to determine from the observational data the magnitude of t_A^2 for the Orion Nebula. Limitations of space here preclude repeating most of the particulars of the data processing and subsequent analysis. For these, the reader is referred to R03.

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2. *HST* OBSERVATIONS

The observations of NGC 1976 described here were taken as part of our *HST* Cycle 7 program GO-7514. We observed with 4 different STIS long-slits: slits 1, 2, 4, and 5. These were shown in the color figure 1 (R03). Slit 1 is located roughly S–SW of θ^1 Ori C. It passes through the position 1SW, which we observed with *HST*/FOS and GHRS earlier and also through the proplyd P159-350 (O'Dell & Wen 1994). Slit 2 is parallel to slit 1 and passes through position x2, one of the most prominent arcs in the [O III] WFPC2 images. Slit 4 crosses the Orion Bar and is oriented to point toward θ^1 Ori C, which also places it essentially orthogonal to the Bar. The southern tip passes through the Herbig-Haro object HH 203. Slit 5 (parallel to slit 4) passes through a very bright, sharply-defined "rim" of the Bar where a positional bifurcation begins.

Observations were made as follows: data for slits 1 and 2 are from Visit 2 (1998 December 7 UT), Visit 52 (2000 December 7) and Visit 72 (2001 December 16); data for slits 4 and 5 are from Visit 5 (1998 December 22). All our data described here were acquired using the STIS/CCD with a 52″ slit length and 0.5″ slit width. At least 2 spectra were taken at each setting in order to cosmic-ray clean. Measurements included the following emission lines (grating setting): [O III] 4364 Å and Hγ 4342 Å (G430M/4451); [O III] 5008, 4960 Å lines and Hβ 4863 Å (G430M/4961); [N II] 5756 Å, (G750M/5734); Hα 6565 Å and [N II] 6550, 6585 Å (G750M/6581). All wavelengths in this paper are vacuum rest wavelengths.

3. DATA ANALYSIS

Before deriving the electron temperature (T_e) from the [O III] and [N II] line ratios, it is necessary to correct the observed line fluxes for extinction.

3.1. *Extinction and Reddening Correction*

This is calculated in terms of $c(\mathrm{H}\beta)$ by comparing the observed $F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)$ ratio with the theoretical intrinsic ratio $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$. We use a value of 2.88 assuming $T_e = 8500$ K and electron density $(N_e) = 5000$ cm^{-3}, Case B (Storey & Hummer 1995). For the Orion extinction curve, we use Martin et al. (1996), with pertinent values provided in R03. For the STIS data, we binned in groups of 10 pixels along the slit into tiles that are 0.5″ square (matching the slit width). This produced $c(\mathrm{H}\beta)$ results for the various tiles, depending on the slit/visit observed, which are the same set used later for the T_e analysis. The distributions of $c(\mathrm{H}\beta)$ along the two slits (slit 1 and slit 2) observed in 3 separate visits (V2, V52, and V72) are remarkably similar.

3.2. *[O III] and [N II] Electron Temperatures*

The T_e values for [O III] and [N II] are derived from the intrinsic flux ratios $I(5008)/I(4364)$ and $I(6585)/I(5756)$ respectively. While the derivation of the former will be nearly invariant to knowledge of N_e for Orion (with the exception of dense objects such as P159-359 here), we do need to be concerned with the value for N_e when deriving T_e [N II], because the critical density (N_{crit}) for the 6585 line, $\sim 7.7\times10^4$ cm^{-3} (at 10^4 K), is substantially less than N_{crit} for the [O III] 5008 line ($\sim 6.4\times10^5$ cm^{-3}). For T_e [N II], we consider various N_e values. We also derive this T_e utilizing two different sets of N II effective collision strengths – those calculated by Lennon & Burke (1994) and by Stafford et al. (1994).

As is well known, there is an inverse scaling of [N II] T_e with N_e. First we perform the calculations for T_e in the low-N_e limit. This provides a firm upper limit to the T_e distributions evaluated for the various slit/visit data. In R03, we also repeated the full computations for 4 more N_e's: 1000, 2000, 5000, and 10000 cm^{-3}. Here we provide 4 new calculations for 4 other N_e's: 3000, 4000, 8000, and 15000 cm^{-3}. We extend to higher densities in order to more conservatively bracket the high-N_e expectations for Orion (excepting objects like the proplyds). Rodríguez (1999) found N_e [S II] as high as 14600 cm^{-3} (at long-slit position M42 A-1, see her fig. 1). This is in the bright area of Orion near our position 1SW. The value of 5000 cm^{-3} was our best single N_e to cover the region of slits 1 and 2 (e.g., Pogge, Owen & Atwood 1992). Their map of N_e [S II] indicates that N_e is lower in the regions of our slit 4 and slit 5; for these, we had adopted a best single N_e = 2000 (R03). Preliminary N_es derived for each tile using [S II] $F(6733)/F(6718)$ indicate that 3000 cm^{-3} may be a more appropriate average for slits 4 & 5. For slits 1 & 2, the tiles in the vicinity of 1SW reach $N_e \sim 8000$ cm^{-3}. Thus, we have added computations for 3000, 4000, and 8000 cm^{-3} here.

4. RESULTS, DISCUSSION, AND CONCLUSIONS

The observations here do not address T_e fluctuation along the line of sight (*los*) through the specific O^{++} region or, likewise, through the N^+ region. We analyse both the [O III] and [N II] data sets to derive the average T_e and fractional mean-square T_e variations in the *plane-of-the-sky*, which we call $T_{0,A}$ and t_A^2. There is discussion in both Paper I and

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Table 1. Values of $T_{0,A}$ and t_A^2

	O^{++}	N^+									
Slit, Visit	N_e **(cm^{-3})** [a]	**0**		**3000**		**4000**		**8000**		**15000**	
Slit 1, Visit 2	**8151**[b]	**11104**	**(10605)**[c]	**10473**	**(10182)**	**10288**	**(10053)**	**9650**	**(9590)**	**8819**	**(8942)**
	1.04[b]	**0.860**	**(0.795)**	**0.817**	**(0.768)**	**0.804**	**(0.760)**	**0.753**	**(0.728)**	**0.678**	**(0.676)**
Slit 1, Visit 52	**8232**	**11236**	**(10727)**	**10596**	**(10298)**	**10408**	**(10167)**	**9761**	**(9698)**	**8917**	**(9041)**
	0.887	**0.647**	**(0.592)**	**0.608**	**(0.568)**	**0.596**	**(0.560)**	**0.551**	**(0.531)**	**0.487**	**(0.486)**
Slit 1, Visit 72	**8258**	**11232**	**(10723)**	**10591**	**(10292)**	**10403**	**(10161)**	**9754**	**(9692)**	**8910**	**(9033)**
	0.925	**0.765**	**(0.703)**	**0.722**	**(0.676)**	**0.708**	**(0.668)**	**0.658**	**(0.635)**	**0.585**	**(0.584)**
Slit 2, Visit 2	**8142**	**11171**	**(10665)**	**10533**	**(10237)**	**10346**	**(10107)**	**9701**	**(9639)**	**8861**	**(8984)**
	1.15	**1.05**	**(0.956)**	**0.981**	**(0.916)**	**0.961**	**(0.903)**	**0.887**	**(0.854)**	**0.780**	**(0.811)**
Slit 2, Visit 52	**8074**	**10675**	**(10208)**	**10074**	**(9804)**	**9898**	**(9681)**	**9292**	**(9240)**	**8505**	**(8624)**
	1.29	**1.60**	**(1.48)**	**1.51**	**(1.42)**	**1.49**	**(1.40)**	**1.38**	**(1.33)**	**1.23**	**(1.23)**
Slit 2, Visit 72	**8358**	**10909**	**(10424)**	**10290**	**(10008)**	**10109**	**(9881)**	**9484**	**(9427)**	**8671**	**(8792)**
	0.682	**1.43**	**(1.31)**	**1.35**	**(1.26)**	**1.32**	**(1.25)**	**1.23**	**(1.18)**	**1.09**	**(1.09)**
Slit 4, Visit 5	**7790**	**9473**	**(9107)**	**8979**	**(8772)**	**8834**	**(8669)**	**8335**	**(8304)**	**7686**	**(7792)**
	1.57	**0.985**	**(0.918)**	**0.937**	**(0.886)**	**0.921**	**(0.877)**	**0.864**	**(0.839)**	**0.779**	**(0.779)**
Slit 5, Visit 5	**7678**	**9789**	**(9394)**	**9262**	**(9037)**	**9107**	**(8929)**	**8576**	**(8540)**	**7886**	**(7996)**
	1.76	**1.82**	**(1.69)**	**1.72**	**(1.62)**	**1.69**	**(1.60)**	**1.58**	**(1.53)**	**1.41**	**(1.41)**

[a] **electron density assumed for N^+ emission-line region; 0 denotes the low density limit**

[b] **upper row $T_{0,A}$ (K); lower 100 t_A^2**

[c] **using effective collision strengths from Lennon & Burke 1994 (Stafford et al. 1994)**

R03 of the relationship to the classical T_0 and t^2 of Peimbert (1967). We assume for each square column (projection of 1 STIS tile 0.5″ square on the plane-of-the-sky) that the plasma along the *los* is isothermal at the T(4364/5008) in the case of O^{++} or T(5756/6585) in the case of N^+. For the latter case, we consider a large range of N_e values, which should be sufficient for Orion, in order to produce Table 1. The analysis for each N_e assumes that it is constant for the entire STIS slit length and throughout the sheet projected through the nebula along the *los*. In Table 1, we repeat the results for O^{++} and the low-N_e limit for N^+ (R03, table 1), while providing additional entries for N^+ with N_e = 3000, 4000, 8000, and 15000 cm^{-3}.

The major conclusions of this study are:

- Our measurements of T_e reported here are an average along each *los*. Therefore, despite finding remarkably low t_A^2, not larger than 0.0176, we cannot completely rule out much larger temperature fluctuations along the *los*.
- We find [N II] temperatures that are higher than [O III] temperatures. For Orion, this has been known for years (e.g., Baldwin et al. 1991; Rodríguez 1999) and expected on theoretical grounds.
- For P159-350, we find large local extinction based on the dramatic increase in the observed $F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)$ ratio. A comparison of the [O III] 5008 and [N II] 6585 surface brightnesses in the vicinity of P159-350 shows double peaked structure with the 6585 emission much narrower than the 5008 emission. This "inverse H II region" behavior is what is expected due to the external ionization source θ^1 Ori C. The very high derived T_e's at the location of P159-350 are no doubt due more to high N_e values associated with the proplyd than high temperatures.

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