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LETTER

Letter to the Editor

Physical conditions in the partially ionized zone of the Orion nebula⋆

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Abstract. We report the first reliable measurement of the nebular [O I] λ5577 emission line in the Orion nebula. Diagnostic diagrams based on the [O I] $\lambda\lambda$5577, 6300, and [N I] $\lambda\lambda$3467, 5198, 5200 emission lines indicate that the bulk of the nebular emission in the partially ionized zone of the Orion nebula is produced in regions with low to moderate electron densities (2×10^3 – 4×10^4 cm^{-3}) and with electron temperatures in the 8900 to 12400 K range. This result implies that models based on emission originating in high-density partially ionized zones are not applicable to explain the observed [Fe II] spectrum in the optical region.

Key words: ISM: H II regions – ISM: individual objects: Orion nebula – ISM: structure

1. Introduction

The Orion nebula is the brightest and most studied Galactic H II region. Its structure, motions and chemical abundances are known with considerably high detail (e.g. O'Dell 1994; Wen & O'Dell 1995; Osterbrock, Tran, & Veilleux 1992; Esteban et al. 1998, hereafter EPTE).

Recently, Bautista, Pradhan, & Osterbrock (1994) reported the presence of high density regions in the Orion nebula, $N_{\rm e}$ $\approx$ 10^5–10^7 cm^{-3}, based on diagnostic diagrams using [Fe II] emission lines. In addition, these authors found that the Fe^+ abundances derived from different [Fe II] lines measured by Osterbrock et al. (1992) present a lower dispersion when high electron densities are considered. Bautista et al. (1994) argued also that the [Fe II] emission is probably produced in the partially ionized zone (PIZ) and that these high density zones are the denser parts of the ionization front at the edge of the H II region.

The ideas related to the PIZ and to the mechanisms responsible for the excitation of the [Fe II] lines were developed further in a series of papers by Bautista & Pradhan (1995), Bautista, Peng & Pradhan (1996) and Bautista & Pradhan (1998, hereafter BP). BP present a new model with a fully ionized H II region, FIZ, with densities of the order of a few 10^3 cm^{-3} and a dynamic partially ionized H II/H I region, PIZ, at densities of 10^5–10^7 cm^{-3}. In this model the [Fe II] lines originate in both zones the FIZ and the PIZ; while most of the emission of the IR lines originates in the FIZ, most of the emission of the optical lines originates in the PIZ. From this model and based on the [Fe II] lines they find that the Fe/O ratio is between 1/2 and 1/3 solar. By assuming that all the [Fe II] emission is produced in the FIZ they find that the Fe/O ratio is between 1/4 and 1/2 solar

On the other hand, Lucy (1995) finds an alternative explanation for the observed [Fe II] spectrum of the Orion nebula, which is based on the presence of important fluorescence effects on the optical [Fe II] lines. Baldwin et al. (1996) found consistent results with Lucy, reproducing the [Fe II] spectrum in a low density medium considering collisional excitation for the IR lines and fluorescence for the optical ones. Moreover, Rodríguez (1996, 1998) analysed a large number of [Fe II] lines in seven bright galactic H II regions, finding that the observed properties of the [Fe II] spectrum are more consistent with the presence of fluorescence effects, she concludes that the bulk of the [Fe II] emission in the Orion nebula originates in regions with densities of a few 10^3 cm^{-3} and that the abundances derived from the [Fe II] lines are unreliable.

To try to solve this controversy we decided to take a different approach: to determine the physical conditions of the PIZ based on the emission lines of [O I] and [N I]. In this letter we present the first detection in the Orion nebula of the [O I] λ5577 line, the [O I] I(5577)/I(6300+6363) ratio, a measurement of the [N I] I(5198)/I(5200) ratio, and an upper limit for the [N I] I(3467)/I(5198+5200) ratio; we will also discuss the implications of these line ratios for the study of the mechanisms of excitation of the [Fe II] lines. Osterbrock et al. (1992) presented a detection of the λ5577 line which yielded an I(6300+6363)/I(5577) value of 22; however in a subsequent paper Baldwin et al. (1996) obtained a lower limit for $I(6300+6363)/I(5577)$ of 71 from spectroscopic data taken with the Cassegrain echelle spectrograph on the 4 m telescope at CTIO and 29 from spectra taken with the Faint Object Spectrograph on the *Hubble Space Telescope (HST)*; Baldwin et al. (1996) conclude that the [O I] lines presented by Osterbrock et

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⋆ Based on data obtained at the Observatorio Astronómico Nacional, SPM, B.C., México

al. (1992) were severely affected by sky emission and therefore useless for plasma diagnostics.

2. The data

We have reanalyzed the echelle spectra published previously by EPTE and have detected the nebular [O I] λ5577 line. We have also determined an upper limit for the [N I] $\lambda\lambda$3466.51 + 3466.54 lines, hereafter the λ3467 line.

The observations were carried out with the 2.1-m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California, Mexico, on 1995 March 25 and 26. The high resolution spectra were obtained using the REOSC Echelle Spectrograph. This instrument gives a resolution of 0.234 Å pixel^{-1} at Hα using a Tektronic CCD chip of 1024 $\times$ 1024 pixels with a 24 μm^2 pixels size. The spectral resolution is of 0.5 Å FWHM and the accuracy in the wavelength determination of emission lines is about 1-1.5 km s^{-1}.

The observations correspond to slits covering 26.6 $\times$ 2 arcsec^2 in the red and 13.3 $\times$ 2 arcsec^2 in the blue exposures, both slits were oriented in the east-west direction and located at 25 arcsec south and 10 arcsec west of θ^1 Orionis C (position 2 of EPTE). The red spectra cover from $\lambda\lambda$4500 to 6850 in 17 spectral orders; and the blue spectra cover from $\lambda\lambda$3300 to 5800 in 26 spectral orders. A detailed description of the observations and data reduction can be found in EPTE. EPTE do not report the intensities of the lines in the $\lambda\lambda$3300 to 3550 range due to their relatively low signal to noise ratio and partial ovelapping between spectral orders, nevertheless due to the importance of the [N I] λ3467 line, we reanalized our data and present an upper limit for the intensity of this line in Table 1.

These observations represent a clear improvement with respect to the ones obtained by Baldwin et al. (1996). Firstly, the exposure time of the HST spectra (225 s) obtained by these authors is substantially shorter than the one-hour spectrum obtained by EPTE. Secondly, although Baldwin et al. (1996) do not indicate the exposure time of their 4m CTIO data (of similar spectral resolution), the comparison of their spectrum (see their Fig. 1) and our data (Fig. 1 of this letter) indicates the larger signal-to-noise ratio of the spectrum taken at San Pedro Mártir.

3. The physical conditions in the PIZ

The profiles of the three [O I] lines observed in our deep red spectrum are shown in Fig. 1, all these profiles show clear line-splitting. A double Gaussian profile fit procedure was applied to obtain the observational parameters of each component (central wavelength and line intensity). The Gaussian fitting procedure was performed making use of the Starlink DIPSO software package (Howarth & Murray 1990) and the graphical results of the fitting are shown also in Fig. 1. In Table 1 we include the observed (relative to the heliocentric reference frame) and laboratory wavelengths of each component of the [O I] and [N I] lines, and the heliocentric velocity and the derredened line intensity ratios (relative to Hβ) of the nebular component. The adopted reddening coefficient, C(Hβ), for this slit position is

Table 1. Observational parameters of the [O I] and [N I] lines

Ion	$\lambda_{\rm lab}$ (Å)	$\lambda_{\rm obs}$ (Å)	Comp.	$v_{\rm hel}$ (km s^{-1})	I(λ)/I(Hβ)
[O I]	5577.34	5577.34	Sky	...	...
		5577.80	Neb.	+24.6	0.000117
	6300.30	6300.31	Sky	...	...
		6300.79	Neb.	+23.3	0.00806
	6363.78	6363.78	Sky	...	...
		6364.33	Neb.	+25.9	0.00238
[N I]	3467	...	Neb.	...	$<$0.001
	5197.90	5198.37	Neb.	+27.1	0.00160
	5200.26	5200.72	Neb.	+26.5	0.00096

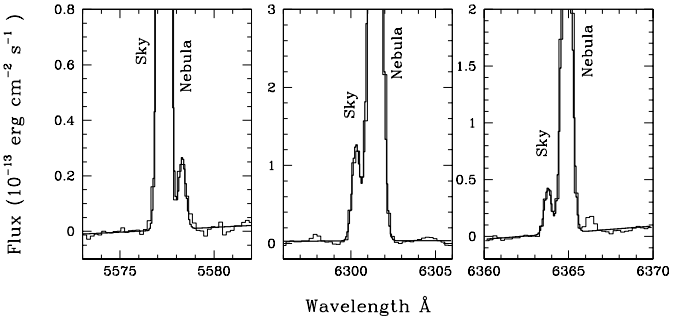

Fig. 1. Examples of double Gaussian fit to the three [O I] emission lines observed. The identification of each component as corresponding to sky or nebular emission is indicated.

0.39 $\pm$ 0.04 and was derived previously by EPTE. As it can be seen in Table 1, the heliocentric velocity of the redshifted component of the [O I] λ5577 line is consistent (within the estimated uncertainty of about 1.2 km s^{-1}) with the velocities of the redshifted components of the other much brigther [O I] lines. The average heliocentric velocity of the bright nebular components is 24.6 $\pm$1.8 km s^{-1}, in agreement with 26.8 $\pm$1.4 km s^{-1}, the average velocity found for the two [N I] lines observed in the same set of data (also included in Table 1), and with the value of 26.7 km s^{-1} obtained by O'Dell & Wen (1992) for the nebular [O I] emission in the same zone. Moreover, the heliocentric radial velocity of the molecules in OMC 1 (the molecular cloud associated to the Orion nebula) is close to 27 km s^{-1} (Goudis 1982). All these observational facts indicate undoubtedly that the redshifted component of the [O I] λ5577 line is truly nebular and should arise in the transition zone of the nebula, as it was stated by O'Dell & Wen (1992).

In Fig. 2 we present a $T_{\rm e}$ versus $N_{\rm e}$ diagram based on the [N I] and [O I] line ratios presented in Table 1. The $T_{\rm e}$ and $N_{\rm e}$ values for the different line ratios have been computed using the five-level program for the analysis of emission-line nebulae of Shaw & Dufour (1995) together with the atomic data compiled by Pradhan & Peng (1995). The $I(6300+6363)/I(5577)$ ratio provides us with a relationship between $N_{\rm e}$ and $T_{\rm e}$, therefore we need at least another observational constraint to determine $N_{\rm e}$ and $T_{\rm e}$. The [N I] $I(5198)/I(5200)$ ratio is close to $N_{\rm e}$ saturation limit and can not provide us with an upper limit for $N_{\rm e}$, but

Table 2. Properties of the Orion nebula: models and observations

	Model			
	BFM[1]	RSHE[2]	Observations[3,4,5]	Observations[3,4,6]
O/H	3.81×10^{-4}	4.0×10^{-4}	4.37×10^{-4}	
N/H	8.7×10^{-5}	6.8×10^{-5}	6.03×10^{-5}	
N/O	0.228	0.170	0.138	
O^0/O	3.46×10^{-3}	1.74×10^{-2}	3.30×10^{-3}	4.90×10^{-3}
N^0/N	7.81×10^{-4}	2.09×10^{-2}	$(0.86 - 2.79)\times10^{-2}$	$(0.61 - 3.5)\times10^{-2}$
N^0/O^0	0.052	0.204	0.36 - 1.17	0.17 - 0.99
O^0/H^+	1.31×10^{-6}	6.96×10^{-6}	1.44×10^{-6}	2.12×10^{-6}
N^0/H^+	6.79×10^{-8}	1.42×10^{-6}	$(0.52 - 1.68)\times10^{-6}$	$(0.37 - 2.1)\times10^{-6}$
$N_e(N^0, O^0)$ (cm^{-3})	≈6000	≈4000	...	...
T_e([O I]) (K)	9900	≈7500	10400^{+2000}_{-1100}	10000^{+1800}_{-1100}
N_e([N I] 5198/5200) (cm^{-3})	...	...	>2000	>4350
N_e([N I] 3467) (cm^{-3})	...	...	<38000	<35800
N_e([S II]) (cm^{-3})	...	...	6410^{+3010}_{-2900}	

[1] Baldwin et al. (1991); [2] Rubin et al. (1991); [3] Esteban et al. (1998); [4] This paper; [5] Mendoza (1983); [6] Pradhan & Peng (1995)

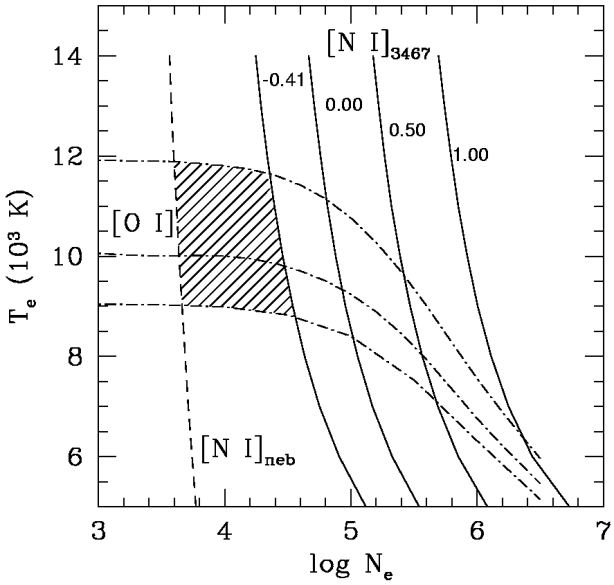

Fig. 2. Temperature (K) vs. density (cm^{-3}) diagram for the PIZ in the direction of position 2. The vertical dashed line corresponds to the minimum density allowed by the [N I] $I(5198)/I(5200)$ ratio. The three dot-dashed lines correspond to the 60, 89 and 118 [O I] $I(6300+6363)/I(5577)$ ratios. The four solid lines correspond to the maximum density allowed by different [N I] $I(3467)/I(5198+5200)$ line ratios; the numbers inside the figure denote log $I(3467)/I(5198+5200)$ values, -0.41 dex corresponds to the determined upper limit for position 2 in this paper. The permitted T_e and N_e values are represented by the shaded area.

gives us the lower limit for N_e presented in Fig. 2, where we have adopted a lower limit of 1.39 for the [N I] $I(5198)/I(5200)$ ratio. Fortunately, we can use the $I(3467)/I(5198+5200)$ ratio to obtain an upper limit for N_e, the computed upper limit for this line ratio is -0.41 dex and is also presented in Fig. 2. In this figure we also present a shadow area that corresponds to the permitted region by the three observational constraints, this region gives N_e in the range 2×10^3-4×10^4 cm^{-3} and T_e: 9000-12000 K.

It is also possible to determine an upper limit for the [N I] λ3467 line intensity from the data presented by Osterbrock et al. (1992). The He I λ3479 line was detected with an intensity of 0.000695 relative to Hβ. By adopting an upper limit for $I(3467)/I(H\beta)$ of 0.0007, the $I(5198+5200)/I(H\beta)$ value reported by Osterbrock. et al., and a T_e = 10000 we find that $N_e < 3\times10^4$ cm^{-3}, in agreement with our estimations above. Kaler, Aller & Bowen (1965) did not detect the λ3467 line either and a similar upper limit for N_e can de derived from their observations.

From the atomic data compilation by Mendoza (1983) a similar figure to Fig. 2 can be obtained. Note that the rate coefficients for electron impact presented by Mendoza for N I and O I are the same as those presented by Pradhan & Peng (1995), while the radiative transition probabilities presented by Mendoza are more recent than those presented by Pradhan & Peng. In Table 2 we present some abundance ratios and physical parameters derived from the atomic data sets compiled by both groups of authors.

In Table 2 we also present some characteristics of the models by Baldwin et al. (1991, hereafter BFM) and Rubin et al. (1991, hereafter RSHE), together with properties derived from observed line ratios. BFM presents properties averaged over radius, while RSHE properties averaged over the entire volume of the H II region; in these models the O/H, N/H and $N_e(H^+)$ values are assumed to match observed line intensities, while the O^0/H^+, N^0/H^+, $N_e(N^0, O^0)$ and T_e values are predicted by the models.

We define $N_e(N^0,O^0)$ and T_e([O I]) as the values derived from the forbidden line intensities predicted by the models. Unfortunately BFM and RSHE do not present explicitly the values of $N_e(N^0,O^0)$ and T_e([O I]) but they can be estimated from the

figures and tables given by them. In the partially ionized zone T_e varies from a maximum value given by T_e([O II]) to practically zero. The average temperature in the O I zone, 6215 K, given by RSHE is a lower limit to T_e([O I]) because the temperature dependence of the emission lines is not included in their determination. The T_e([O I]) value for the BFM model was derived from the [O I] $I(5577)/I(6300)$ ratio predicted by Baldwin et al. (1996) for Model A and the atomic data compiled by Mendoza (1983).

The observed O^0/O, T_e([O I]), and O^0/H^+ values are in excellent agreement with the values predicted by the BFM model. On the other hand, the N^0/O^0 observed value is in good agreement with the RSHE one and considerably higher than the BFM value. Note that if N_e were higher than 4×10^4 cm^{-3} the N^0/O^0 value derived from observations would become even higher than the maximum values presented in Table 2, increasing the discrepancy between the models and the observations.

From photoionization models and partially due to the ionization potentials of O I (13.6 eV), N I (14.5 eV), Fe II (16.2 eV), and S II (23.3 eV), the [O I] and [N I] lines are expected to originate farther away from the ionizing stars than the [Fe II] lines, and even farther than the [S II] lines. Therefore, the average density where the [Fe II] lines originate should be intermediate between those derived from the [N I] lines and the [S II] lines, which according to Table 2 is considerably smaller than the density derived by BP from the [Fe II] lines under the assumption that fluorescence effects are negligible. To obtain N_e = 10^6 cm^{-3} the [N I] λ3467 line has to be at least an order of magnitude brighter than the upper limit presented in Table 1 (see Fig. 2).

4. Summary

In this *Letter*, we report the first reliable detection of the nebular [O I] λ5577 line in the Orion nebula. Based on [O I] and [N I] line ratios we have found that these lines originate in the PIZ with $2000 < N_e$ (PIZ) < 40000 cm^{-3} and $8900 < T_e$(PIZ) < 12400 K. From photoionization models it follows that the N_e (Fe II) value should be intermediate between that given by N_e(PIZ) and N_e (S II) and consequently that $2000 < N_e$ (Fe II) (PIZ) < 40000 cm^{-3}. These low densities probably indicate that fluorescence effects are important in the excitation of [Fe II] lines in the optical region. Consequently the Fe/O abundances derived from the Fe^+/O^0 ratios under the assumptions that fluorescence effects for the [Fe II] lines are negligible and that N_e (Fe II) $\sim 10^6$ cm^{-3} are unreliable.

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References

Baldwin, J. A. et al. 1996, ApJ, 468, L115
Baldwin, J. A., Ferland, G. J., Martin, P. G., Corbin, M. R., Cota, S. A., Peterson, B. M., Slettebak, A., 1991, ApJ, 374, 580 (BFM)
Bautista, M. A., Pradhan, A. K., 1995, ApJ, 442, L68
Bautista, M. A., Pradhan, A. K., 1998, ApJ, 492, 650 (BP)
Bautista, M. A., Peng, J., Pradhan, A. K., 1996, ApJ, 460, 372
Bautista, M. A., Pradhan, A. K., Osterbrock D. E., 1994, ApJ, 432, L135
Esteban, C., Peimbert, M., Torres-Peimbert, S., Escalante, V., 1998, MNRAS, 295, 401 (EPTE)
Howarth, I. D., Murray, J., 1990, SERC Starlink User Note No. 50
Goudis, C., 1982, The Orion Complex: A Case Study of Interstellar Matter (Dordrecht: Reidel)
Kaler, J. B., Aller, L. H., Bowen, I. S., 1965, ApJ, 141, 912
Lucy, L. B., 1995, A&A, 294, 555
Mendoza, C., 1983, IAU Symp. 103, Planetary Nebulae, Flower D.R. (ed.), Dordrecht, Kluwer, 143
O'Dell, C. R., 1994, Ap&SS, 216, 267
O'Dell, C. R., Wen, Z., 1992, ApJ, 387, 229
Osterbrock, D. E., Tran, H. D., Veilleux, S., 1992, ApJ, 389, 305
Pradhan, A. K., & Peng, J, 1995, The Analysis of Emission Lines, Williams R. E., Livio M. (eds.), Cambridge University Press, p. 8
Rodríguez, M., 1996, A& A, 313, L5
Rodríguez, M., 1998, PhD. Thesis, Universidad de La Laguna
Rubin, R. H., Simpson, J. P., Haas, M. R., Erickson, E. F., 1991, ApJ, 374, 564 (RSHE)
Shaw, R. A., Dufour R. J., 1995, PASP, 107, 896
Wen, Z., O'Dell, C. R., 1995, ApJ, 438, 784